THE JOURNAL OF SOLID WASTE TECHNOLOGY AND MANAGEMENT

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October 2025 **Volume 51** **Special Issue 4 - 1**

Special Issue 4-1: 15th IconSWM-CE & IPLA Global Forum 2025;

Graphic Era (Deemed to be University), Dehradun, India

Waste Valorisation and Resource Circularity

ISWMAW International Society of Waste Management, Air and Water

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Editor-in-Chief and Guest Editors

Editor-in-Chief

Prof. Sadhan Kumar Ghosh
DG, Sustainable Dev. & Circular Economy Research Centre, ISWMAW,
& Ex- Dean, FET, Jadavpur University, India

He is recognized & enlisted among Top 2% Scientists in the World 2025-2025) and is among the Top Scholar - Prior 5 Years ranks in 0.5% in the world: # 17 in Waste Management, #84 in circular economy and #141 in Sustainable Development as per ScholarGPS 2025. He is globally renowned personality in the field on Waste Management, Circular Economy, Green Manufacturing, Sustainable Development, Co-processing, Plastics & E- Waste management, Recycling, ISO Standards & TQM having collaboration in 45 countries. He provided expert services to more than 150 industry units in India, Taiwan, Japan, Sri Lanka, Denmark, and the UK. Editor of a few reputed Journals; edited 45 books, wrote 10 books & 350 national and international articles & book chapters, possess 3 patents, member in Indian mirror committee of ISO TC 323 - Circular Economy, ISO/TC297- Waste collection and transportation Management & ISO TC 207- EMS in BIS, was ISOTC 61WG2 convener. He is considered the leading expert in encouraging waste co-processing in Cement plants through "*IconSWM-CE Excellence Award"* scheme that he initiated. He conceptualised a mission, "*Catch Them Young: Zero Waste & Circular Economy in Campus*" involving 380000 students & teachers in India, Nepal, Georgia and Kenya - a first initiative ever of inducing circular economy among school students.

Guest Editors

Prof. (Dr.) Narpinder Singh
Vice Chancellor, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India

Prof. Narpinder Singh is a globally renowned food scientist and Fellow of the Royal Society of Chemistry (FRSC, 2022). A Ph.D. (Food Technology) from Punjab Agricultural University, he currently serves as Vice Chancellor of Graphic Era (Deemed to be University), Dehradun. Ranked among the Top 2% Scientists in the World (2020–2025) by Elsevier–Stanford, he holds #23 position globally in Food Science, and No. 1 in India in Agriculture, Fisheries & Forestry and Food Science. With over 425 publications, 35,000+ citations, and an h-index above 98, he is a Highly Cited Researcher (Clarivate 2021, 2022). Prof. Singh's pioneering work in cereal science, starch and protein chemistry, extrusion technology, modified starches, gluten-free product development, and plant-based meat analogues has transformed food technology research. His recent studies explore metabolomics, foodomics, and structure–function relationships of starches from diverse crops. He has mentored over 40 doctoral scholars and collaborated internationally across the UK, Japan, USA, and China. Recipient of the INSA Young Scientist Medal, Rafi Ahmed Kidwai Award (ICAR) and J.C. Bose National Fellowship (DST).

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PhD in Engineering from Jadavpur University. Prof. Baidya, Head, Office of the Sustainability, Institute of Engineering & Management (IEM), School of University of Engineering and Management Kolkata & Asst. HoD, Dept of Mechanical Eng. at IEM (School of UEM Kolkata) India, was a Research Fellow (Visiting), ABS, Aston University, UK, an executive member of ISWMAW. His research interest includes circular economy, co-processing, resource and energy recovery from waste, SCM & optimization engineering, having 65 publications in refereed journals and in international conferences. He has worked as co-investigator in number of international research projects funded by UKIERI, Royal Academy of Engineering (RAE), British Council and Erasmus+.

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Dr. Manvandra Kumar Singh is an Associate Professor in the Department of Mechanical Engineering at Graphic Era (Deemed to be University), Dehradun, India. He earned his B.Tech. in Mechanical Engineering from UPTU, Lucknow (2009), followed by an M.Tech. in Materials Science and Technology from IIT (BHU) Varanasi (2011), and a Ph.D. in Mechanical Engineering (Design) from the same institute (2018). His research focuses on the microstructural, physical, mechanical, and tribological behavior of biomaterials, metal matrix, and hybrid composites. Dr. Singh has published over 70 journal and conference papers, 15 book chapters, one Springer-edited book, and holds four patents with ten more filed. He serves on several editorial boards, including Scientific Reports (Springer).

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PhD in Biotechnology from Jadavpur University. Dr. Sutripta Sarkar completed her Graduation and Masters from RDVV Jabalpur. Thereafter she joined the Indian Statistical Institute as JRF and later as SRF. She has been working at Barrackpore Rastraguru Surendranath College for more than 14 years and continued publishing her research in reputed journals. She has recently published in Scientific reports and her works are well cited.Over the years she has been teaching in specialized areas like clinical biochemistry, epidemiology and public health, microbiology, research methodology etc. she has attended several international conferences and wonderful best paper awards. She has also being supervising PhD, Postgraduate and Undergraduate students for their thesis.

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Dr. Rachan Karmakar is an Assistant Professor of Environmental Science at Graphic Era (Deemed to be University). His research spans bioenergy, bioremediation, algal-based sustainable development, and fuel emission characterization. He has authored several high-quality publications and holds multiple patents in the field. Dr. Karmakar is also an active member of reputed international scientific societies, including the Royal Society, contributing to global discourse on sustainability and environmental innovation.

PREFACE

This special issue represents a collection of studies that includes different valorisation processes demonstrating circularity of resources employing innovative technologies. The issue contains three editorial presenting the recent research trends in agricultural waste management and microbiology in waste Management. Artificial Intelligence (AI) has become a very important areas of intervention in all spheres of life. One editorial highlight how the AI tools can be applied in waste management. Nine articles and three editorials included in this special issue on 15th IconSWM-CE & IPLA GF 2025.

Research output of use of extracts of fruit seed and waste leaf have been presented by the authors in two articles. One article presents on the quorum sensing (QS) modulation potential of Emblica officinalis seed extract against the Pseudomonas aeruginosa. The study showed the potential of E. officinalis as an environmentally sound QS inhibitor, leading to a framework of waste valorization and circular biotechnology. Another study explored the potential of using spinach leaf extract as an environmentally effective corrosion inhibitor for copper, presenting sustainable materials research within the circular economy framework. In this study, the waste spinach leaves were extracted in ethanol and then applied to a copper surface via drop-casting in multiple layers. This led to the findings the drop casting of the copper with the spinach extract comprising of the biomolecules provided an effective protective layer. This innovative utilization of household waste shows that, simple nature-based solutions can incorporate sustainability into corrosion science.

Three articles have presented the research and policy related to energy recovery. Waste-to-energy (WtE), commonly via a combustion-based process, is an effective component of a modern waste management strategy, whereby landfill-bound waste streams are converted to heat and power. The technologies supporting these pathways are mature and well-developed and have for many years contributed positively to sustainable waste management processes. Non-Recyclable Plastic Waste (NRPW) in the waste stream is a vulnerable area which significantly contribute to marine littering. A study reported the policy framework and technical intervention on the scaling up of NRPW utilisation in WtE plants and in cement plants in India. The study shows the co-processing and WtE are complimentary end-of-life pathways that enable energy recovery, coal substitution, and landfill diversion within a circular economy principle. Cuttack is one of the twin cities with the capital city of Odisha. A study presented the infrastructural and financial challenges of municipal solid waste management of Tier-II cities compared to metropolitan cities.

The special issue highlights the technological innovations in waste valorization specifically focusing on agro industrial waste valorization. One article presents study on mathematical modeling of microbial fuel cells, combining microbial growth kinetics, substrate degradation, and electron transfer mechanisms for predicting bioelectricity generation while utilizing pure lactic acid and cottage cheese whey. Another study presents a techno-economic analysis of biochar-assisted anaerobic digestion of food waste, the research finding showed higher methane yields and more revenue generation. A very interesting study analysed Tea waste, an abundant agro-residue waste, for adsorption of methylene blue dye—a common pollutant in paper and textile industries—and subsequently served as a substrate for the production of the industrial enzyme laccase using *Phanerochaete chrysosporium*. Further studies on bacterio-algal fuel cells, demonstrated the efficacy of bio-based and low-cost solutions for reduction of pollution while simultaneously generating value-added products from the waste thus enhancing circular economy approach. One of the studies in Georgia reveals the challenges in implementing reforms with regards to waste management and Extended Producer Responsibility (EPR) in their national policy system particularly when considering a transition economy.

The studies in this special issue presents an insight on the multi-scalar characteristic of circularity and its transition, indicating the effective implementation of sustainability measures in community projects, valorisation of agro industrial waste and policy framework. The contributions further reveal the barriers like - fragmented governance, weak enforcement, limited infrastructure, and financial obstacles. The studies also on the positive side present practical approach, evidence-based solutions which can be adopted across the contexts.

This special issue contains the research articles which offer a comprehensive finding which advances the understanding of circular economy principles and waste valorisation techniques and their implementation in developing countries.

Editorial - 1

Prof. Dr. Narpinder Singh
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Agricultural Waste and Its Management: Research Trends and Knowledge Structure

Agricultural activities produce large volumes of waste, including crop residues, animal manure, and agro-industrial by-products. Inappropriate management of these wastes contributed to greenhouse gas emissions, soil and water pollution, and loss of valuable biomass resources. At the same time, agricultural waste offers opportunities for bioenergy, compost, biochemicals, and sustainable resource recovery. Agriculture inhabits around half of the global habitable land and is essential to the economies of numerous countries, particularly the developing ones as it employed a substantial percentage of the workers (Ellis et al., 2010). This important segment possesses a substantial environmental impact. Agriculture is both a cornerstone of human civilization and a major driver of environmental change. Alongside the production of food, fiber, and fuel, it generates vast amounts of agricultural waste—ranging from crop residues and animal manure to agrochemical packaging and food processing by-products. Mismanaged, these wastes can lead to soil degradation, greenhouse gas emissions, water pollution, and public health hazards. This disturbing trend litters valuable resources and significantly adds to greenhouse gas emissions causing environment deterioration and resource diminution (Karmakar et al., 2025). At the same time, agricultural waste offered opportunities for bioenergy, compost, biochemicals, and sustainable resource recovery. In this context, agricultural waste management emerged not merely as a technical necessity but as a strategic imperative for global sustainability. Recognizing this, bibliometric analysis was done during the last five years to get recent insight into the global research landscape on this subject, offering both a snapshot of progress and a guidepost for the way forward.

Methodology: Mapping Knowledge through Bibliometrics

The study offered a comprehensive, bibliometric, and methodical analysis on agriculture waste management. In the first step the goals and constraints of the study were decided. The scope was kept fairly broad in order to include all study aspects related to agricultural waste and its management. The next step was the selection of an appropriate database for data collection. The Scopus database (https://www.scopus.com/ data retrieved on Sept 22, 2025) was chosen because of its extensive and comprehensive coverage of scientific publications. This type of research required verified bibliometric data, for which Scopus was a widely recognized and reliable source (Baas et al., 2020).

Data acquisition and consolidation

The data collection was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards (Aggarwal et al., 2025). The PRISMA approach was carried out in four stages: identification, screening, suitability, and inclusion. The following criteria were used in the search for relevant and important literature pertaining to agricultural waste and management within an inclusive framework: " TITLE-ABS-KEY(Agriculture waste and management) AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA,"AGRI") AND (LIMIT-TO (EXACT KEY WORD, "Agriculture") OR LIMIT-TO (EXACT KEY WORD, "Waste Management") AND LIMIT-TO (LANGUAGE, "English")) AND PUBYEAR > 2022 AND PUBYEAR < 2026. The initial investigation produced 14671 papers. Only 1884 items were retrieved when the limits were applied.

Predictive analytics and visual representation

VOSviewer (version 1.6.19) and Bibliometrix (version R.4.3.0) were used to examine data that had been retrieved from the accessible literature. Bibliometrix software, designed specifically for relevant network analysis and representation was explored (Chen and Gong, 2022). The Scopus database provided the preliminary bibliographic data, which was compiled in a [.csv] file. Biblioshiny web application was launched following the installation and configuration of the Bibliometrix R package in R Studio (Uyanga et al., 2023). The Biblioshiny tool was employed to construct visual representations of the density distribution profile of author collaboration, phrases, and current subjects (Semwal et al., 2024). Additionally, utilising VOS viewer as a tool, a study of author co-authorship, author keyword overlap, and bibliographic coupling across documents was conducted. This free VOS viewer, developed by the Leiden University Centre for Science and Technology Studies, facilitated the mapping and visualisation of bibliometric grids (Van Eck and Waltman, 2011).

Results and Discussion

Overview of dataset

Figure 1 illustrates the 1884 original publications that make up the global scientific output in agricultural waste and management research for sustainable future. Only works published in English between 2022 and 2025 were included in the Scopus database in this body of work. The articles that particularly address the various types of agricultural waste, toxicity towards environment, solutions and challenges related to waste management were included. Notably, these 1884 publications had an average age of 1.5 years, were scattered among 325 different sources, and were written by 13417 authors.

Figure1: Overview of information associated with agriculture waste and management

Territorial analysis of research

The contributions from 96 countries demonstrated the enormous relevance of agricultural waste and management research and showed its worldwide reach. Countries were categorised as either developing (less than publications) or significant (more than 500 publications) based on the volume of articles they produce. The field was led by China, India and USA with Italy, Spain, following. This suggested a connection between a country's ability to manage the agricultural waste. The scientific production map (Fig 2a) showcased the worldwide contribution in this section along with Fig 2b depicting global commitment dedicated towards sustainable future, funded by international efforts, the thriving network of international collaboration consisted of both bilateral partnerships and multi-nation consortia. The worldwide dedication in managing agricultural waste and was demonstrated by the numerous single-country publications.

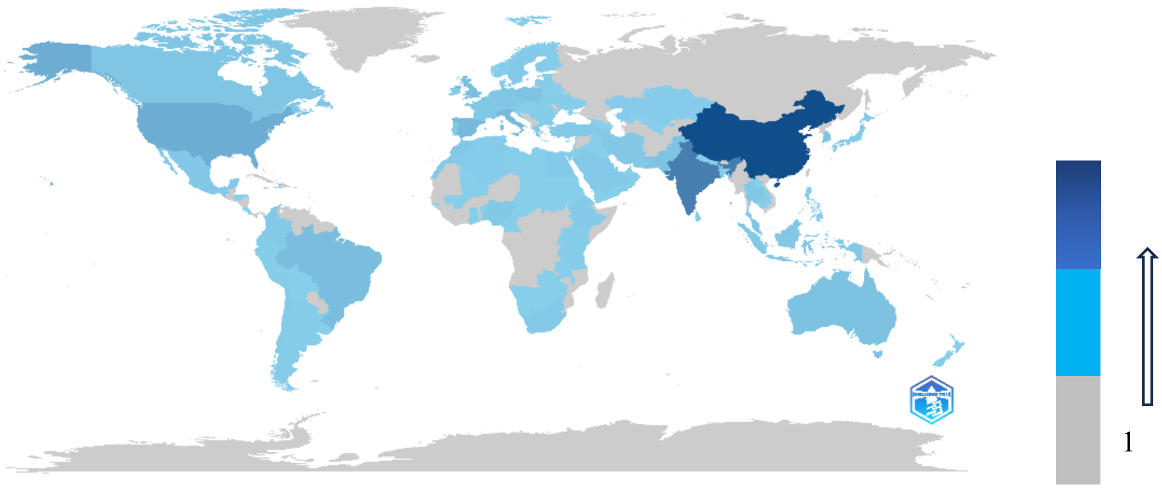

Figure 2: (a) Geospatial distribution of research

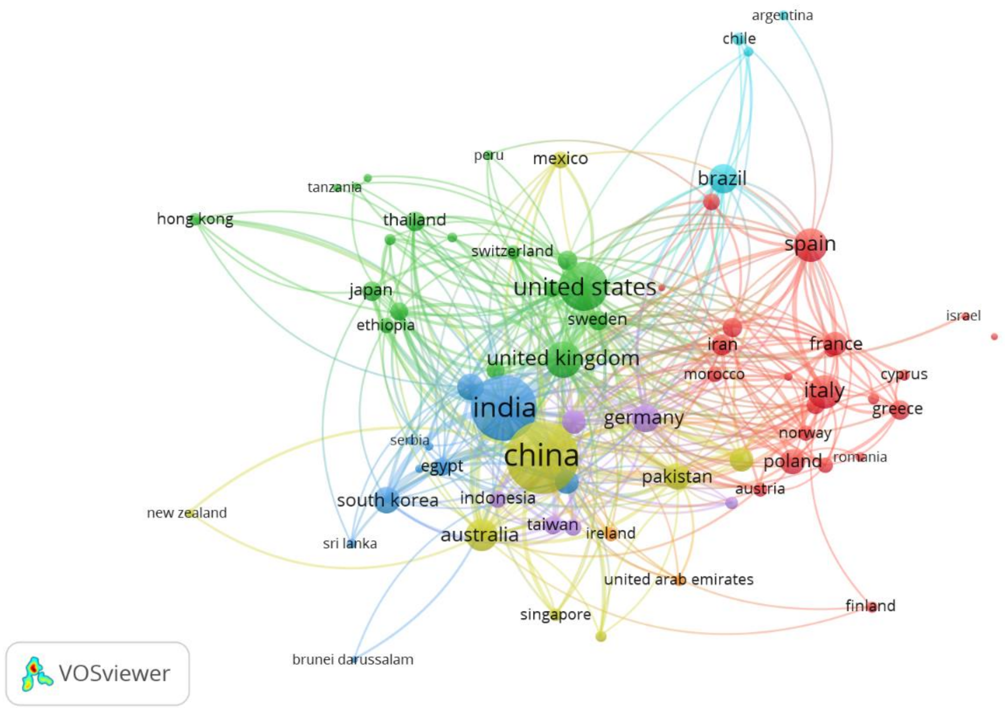

Figure 2: (b) Consortia of collaborating nations

A way to evaluate an author's commitment and output on a research topic is to look at how many papers they have written (Aggarwal et al., 2025). The researchers published 13417 articles in the specialised field of "Agricultural waste and management". Chojnacka Katarzyna W. made the most contribution to this topic, (Fig 3a) with 12 published articles totalling 2.06 fractionalised articles, followed by Izydorczyk, Grzegorz with 8 publications, and Thoaidis Nikolaos S. with just 1 article and 0.10 fractionalised articles. Author collaboration was depicted in a co-authorship network map Fig 3b produced using the VOS viewer. Researchers who had at least ten citations were included in this study, yielding a collection of 577 researchers that met this requirement. The most relevant affiliations (Fig 3c and d) associated with agricultural waste and management with an ideology to provide sustainable future is China Agricultural University with 136 articles, followed by University of Chinese Academy of Science and Wageningen University and research with 82 and 81 articles respectively, with least article by Okoloogia Ja Maateaduste Instituut with only 1 article.

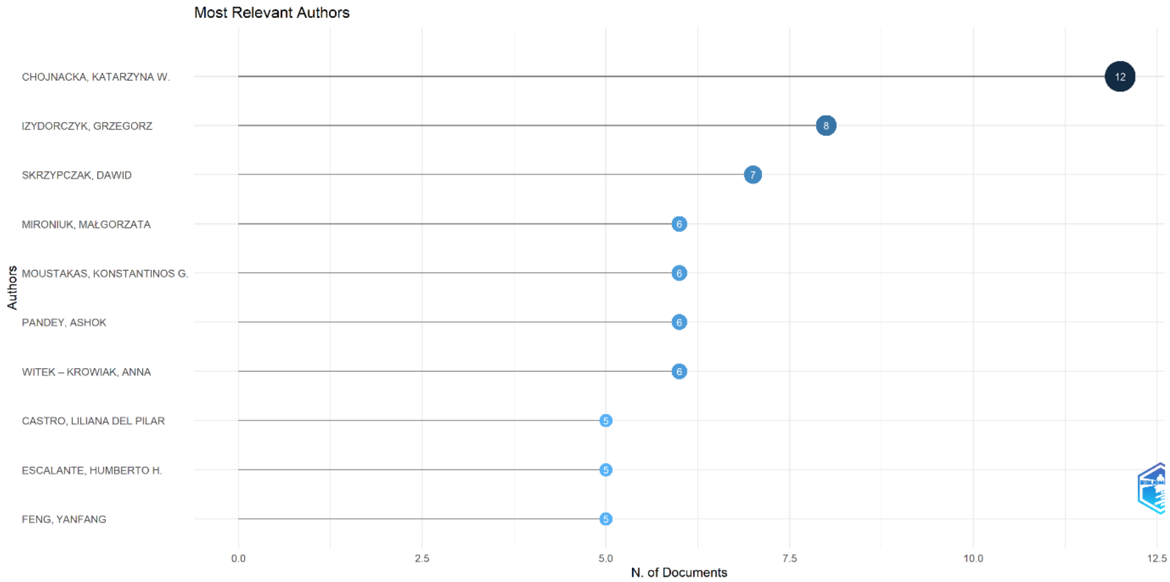

Figure 3: (a) Contributor node sized according to citation impact

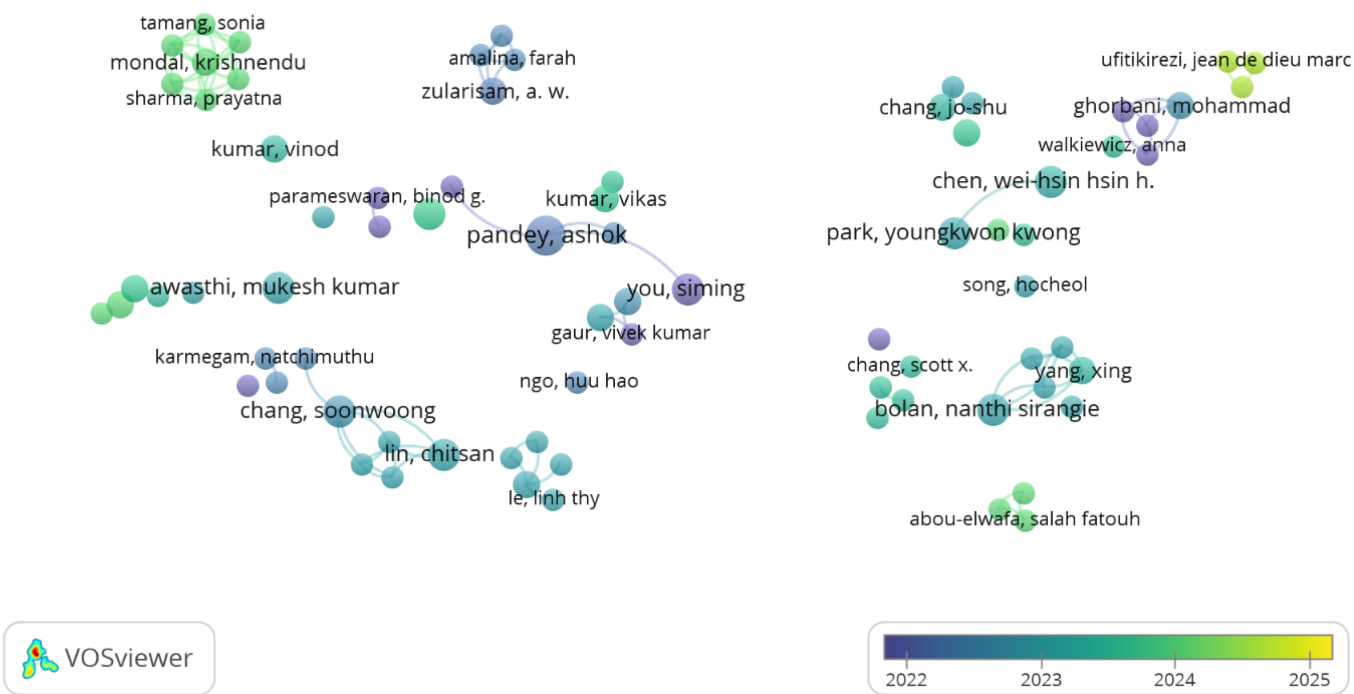

Figure 3: (b) Co-authorship network

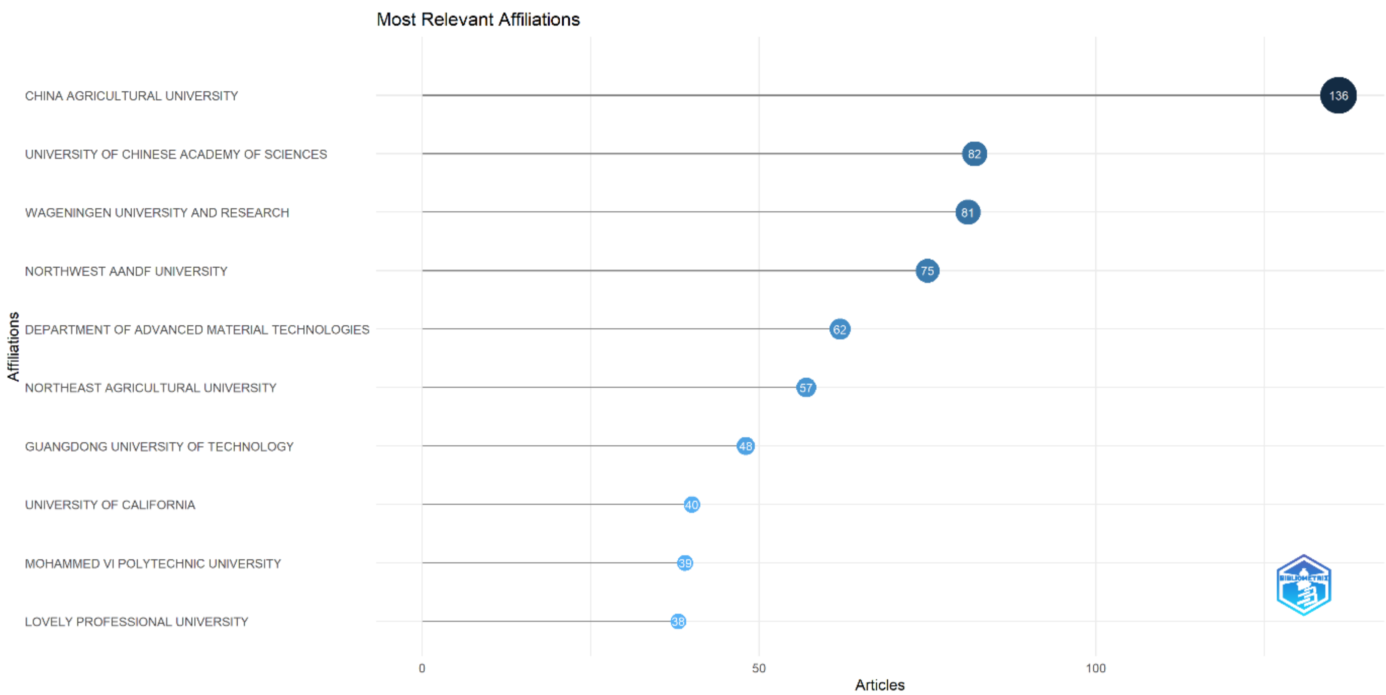

Figure 3: (c) Contributor node for most relevant affiliations

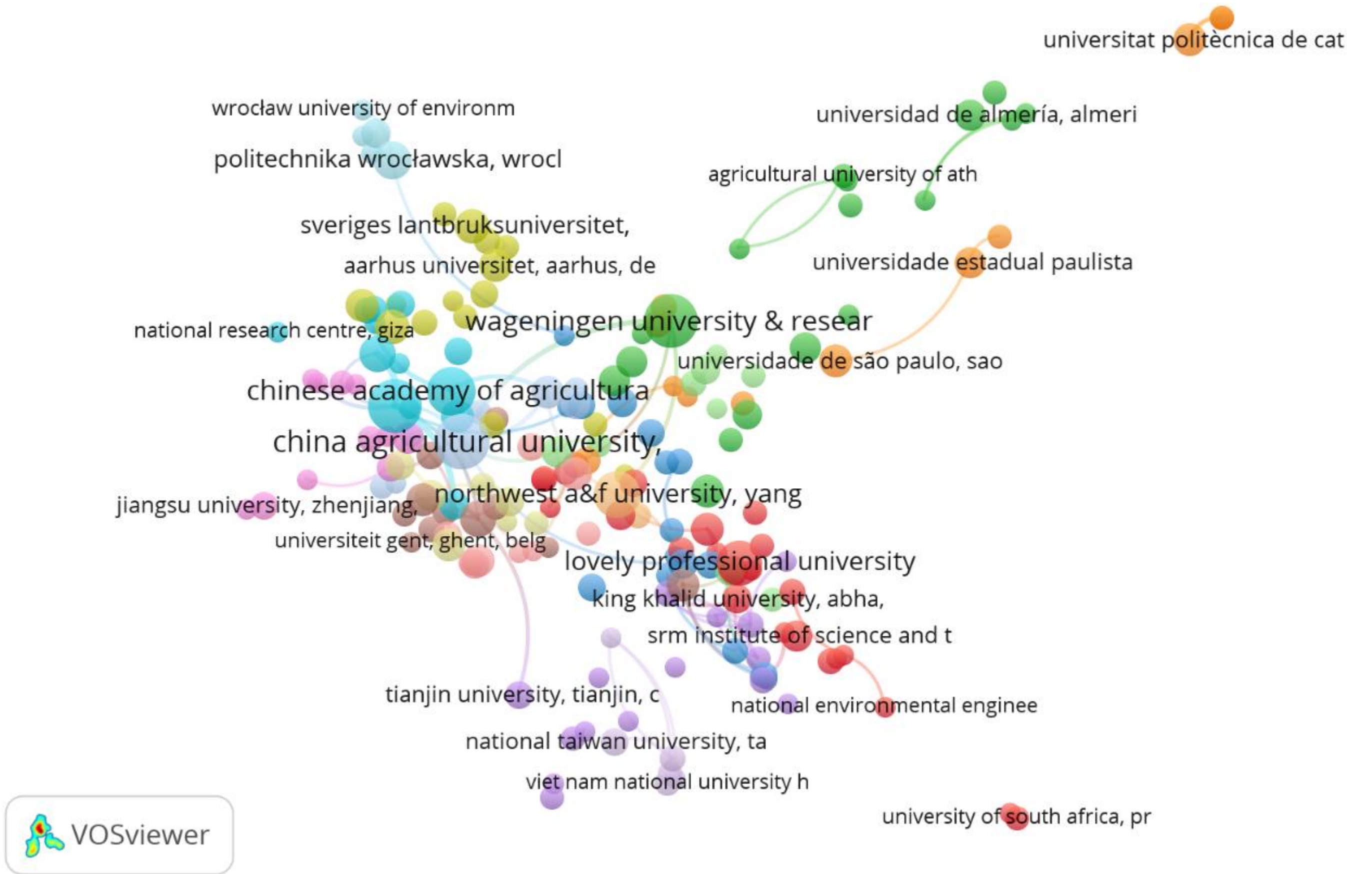

Figure 3: (d) Most relevant contributors

Keyword Scrutiny

Keywords are essential in academic writing since they convey the primary concepts and research subjects. By examining the frequency and occurrence of keywords over time, researchers may monitor trends and investigate new paths (Tripathi et al., 2018). Author keywords and Plus keywords are the two categories of search terms that SCOPUS offers (Aggarwal et al., 2025). The current study focusses on author keyword analysis since titles and author keywords emphasised the primary issues of the research and were crucial for readers and bibliometric studies (Ejaz et al., 2022). Recent advancements in the "Agricultural waste and management" research thrust area were analysed. The objective was to determine the occurrence of keyword usage in these investigations. Of the 18701 keywords that were determined to meet the criterion (Fig 4a), 1253 displayed the co-occurrence keyword map generated by the VOS viewer tool, which effectively identified active research locations. Consequently, 5 clusters were found, each of which stood for a distinct field of study. The ten frequently used search terms are listed in Fig. (4b) together with the average publication rate of the documents and keywords. The analysis of word cloud (Fig 4c) shown terms “waste management” (1003); “non-human” (642); soil (588); “sustainable development” (422) were most re-occuring Keyword Plus terms.

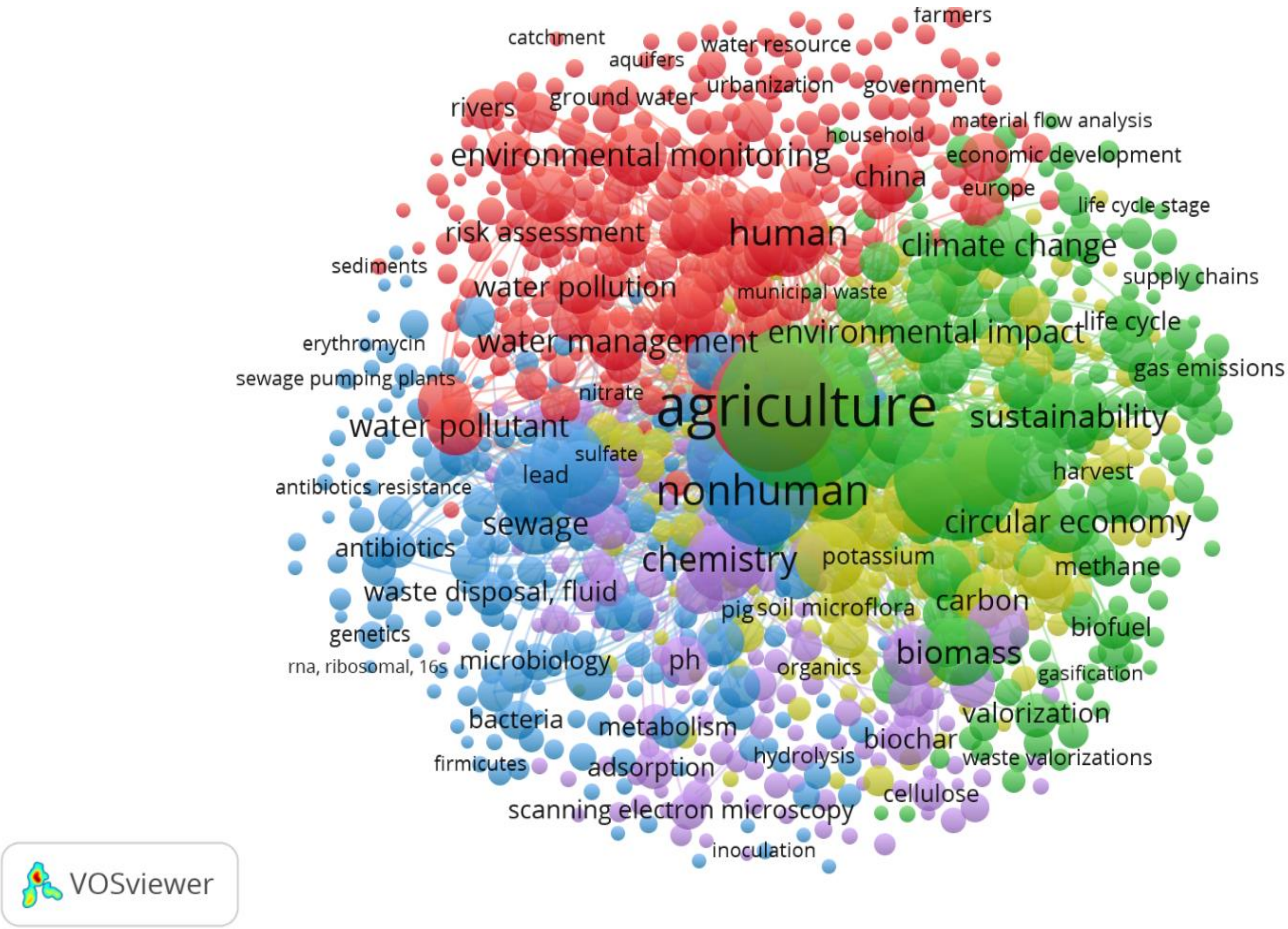

Figure 4: (a) Core keyword cluster

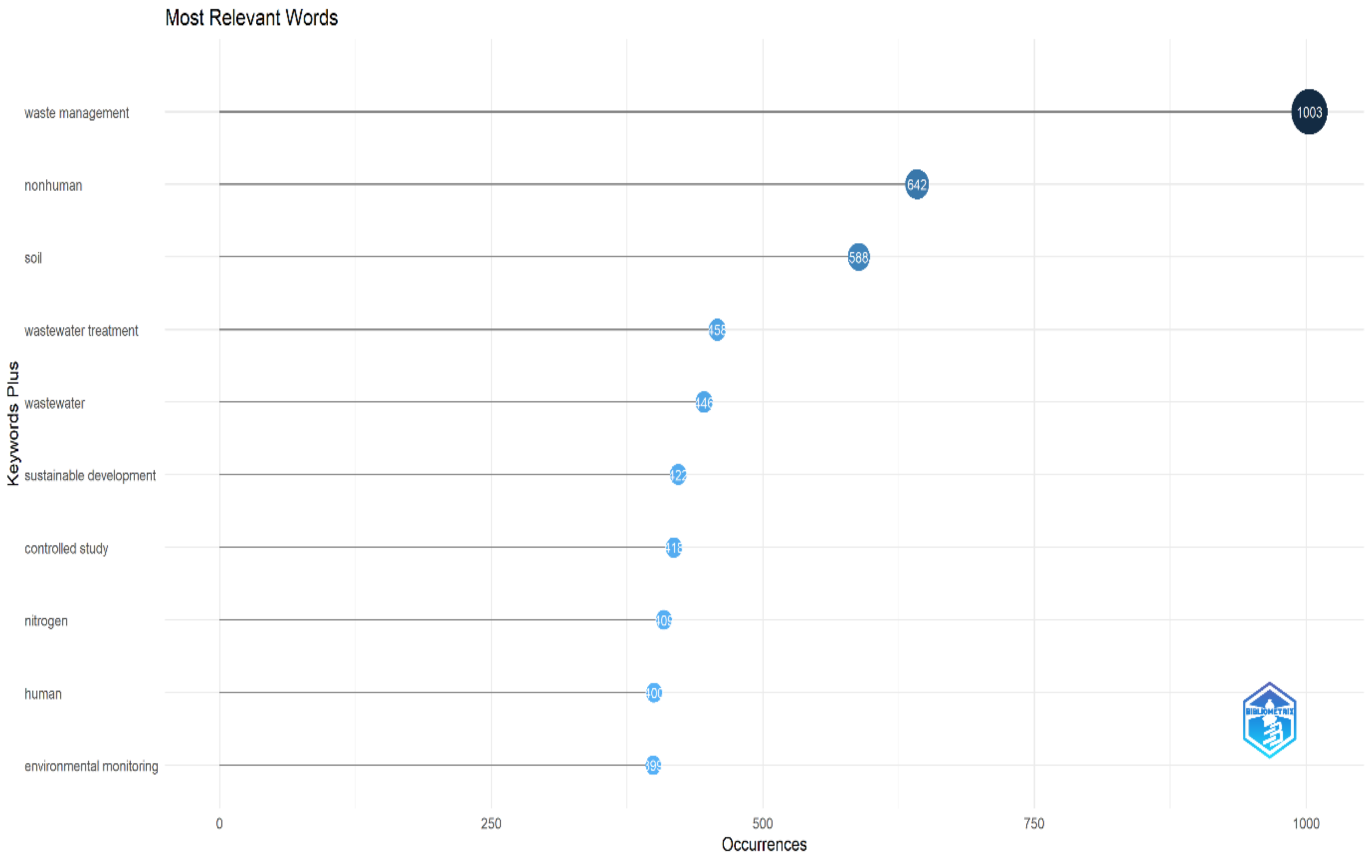

Figure 4: (b) Nodes for author keywords

Figure 4: (c) Word cloud of keywords

Although research on agricultural waste management has grown considerably, several practical and systemic challenges continued. Agricultural waste management had multiple challenges in developing and under developed countries that limit its effective utilization. The predominance of fragmented farming systems, dominated by smallholder farms, generates small volumes of waste in dispersed locations, making collection, transport, and large-scale processing difficult. Conventional agricultural waste management practices, like postharvest open burning of crop remains at farms and the excessive usage of chemical fertilizers, were the key contributors to environmental degradation (Sukuman et al. 2025). The practice of open burning of crops residue in some regions of developing countries produces greenhouse gases and particulate matter, deteriorating air pollution and diminishing soil organic carbon. Likewise, the excessive use of chemical fertilizers upsets soil health, decreases long-term fertility, and pollutes water bodies through leaching of nutrients and eutrophication. These unsustainable practices lead to weakening of the farming system and put food safety and public health at risk. Similarly, small-scale agro-industrial processing restricted the conversion of waste into higher-value products, resulting in significant underutilization. Also, studies remained fragmented across disciplines such as agriculture, energy, agro-processing and environmental sciences, with limited integration into complete management systems. Regional differences also widen the gap, as developing countries— despite being main producers of agricultural waste— contributed relatively less to research output and technology adoption. In addition, weak supply chains and negligible linkages between farmers and industries continue to prevented large-scale investment in waste valorization.

Life Cycle Management (LCM) is vibrant for agricultural waste management as it quantifies environmental, economic, and social impacts across the entire waste-to-resource pathway. Still, gaps persist, including reliance on non-local datasets, weak standardization across diverse waste streams, inadequate integration of socio-economic and biodiversity indicators, and a lack of future oriented modelling. To address these gaps, bibliometric insights informed targeted strategies in both science and practice. Future research need to give more emphasize on the development of integrated valorisation models that combine composting, anaerobic digestion, and bio-refinery approaches to maximize value addition from dispersed waste streams. Equal importance needs to be given to decentralized and scalable technologies, particularly the design of low-cost, small-scale systems suited for fragmented farms and rural contexts. Future research needs to emphasis on developing region-specific life cycle inventories, advancing integrated sustainability assessment methods like Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA) and Life Cycle Sustainability Assessment (LCSA), incorporating ecosystem service valuation, and leveraging digital tools such as AI and blockchain for real-time waste tracking. Addressing these gaps will support the accuracy and applicability of LCM, permitting more efficient and sustainable agricultural waste management systems (Sumiyati et al. 2024; Sukuman et al. 2025; Budihardjo et al. 2023). Sumiyati et al. (2024) emphasize the importance of LCA in evaluating agricultural waste recycling processes. Their study shows that shifting from traditional disposal methods to recycling strategies—such as composting, anaerobic digestion, pyrolysis, and bioenergy production—can significantly reduce greenhouse gas emissions, energy use, and fossil fuel dependence while promoting a circular economy. Among these, biochar stands out as a promising option for waste management, carbon sequestration, and energy generation. However, the study also highlights key gaps, including challenges in collecting complete data and the need to account for secondary impacts like indirect land use change, biodiversity loss, and habitat damage. Sukuman et al. (2025) applied LCA to compare conventional and circular agricultural practices in Thailand. Conventional sugarcane and rice cultivation caused high impacts in resource depletion—while cassava, with existing circular practices, showed lower burdens. Circular approaches, particularly using crop residues for organic fertilizers and animal feed, significantly reduced impacts, cutting significant costs and generating good amount of economic benefit. The study concluded that circular agriculture offered substantial environmental and economic advantages, underscoring the need for supportive policies, technology access, and farmer training to drive large-scale adoption in Thailand. The use of digital and precision tools such as IoT, GIS, and AI required to be involved to further enhance efficiency by improving collection logistics, waste tracking, and LCA. Additionally, socio-economic and policy frameworks need to be strengthened through cooperative models, farmer collectives, and incentive mechanisms that facilitate waste aggregation and shared processing. Embedding sustainability and circular economy linkages within waste management strategies is also critical, especially in relation to carbon neutrality, nutrient recycling, and promoting sustainable rural livelihoods.

Implications for Policy and Practice

The bibliometric findings highlight three critical insights:

1. **Global Priority, Local Challenges:** While developed nations dominate research output, developing countries—often facing acute agricultural waste crises—require greater participation and support to build management frameworks.
2. **Collaborative Knowledge Production:** Networks of co-authorship and institutional partnerships are vital. Expanding South–South and North–South collaborations can accelerate the transfer of sustainable technologies and policies.
3. **Thematic Evolution:** Research trends reflect a shift from isolated waste treatment technologies toward integrated sustainability, circular bioeconomy, and climate-resilient agricultural systems. This aligns with global sustainability goals, but implementation remains uneven.

Conclusion

Agricultural waste and its management remain pressing issues in the Anthropocene. The bibliometric evidence is clear: global research momentum is building, but translating knowledge into practice demands deeper collaboration, context-specific solutions, and supportive policies. As we advance toward 2030 and beyond, the challenge is to ensure that agricultural waste ceases to be an environmental liability and instead becomes a cornerstone of sustainable, circular, and resilient agricultural systems.

The path forward will require not only technological innovation but also political will, farmer engagement, and international solidarity. If effectively harnessed, agricultural waste management could transform global agriculture from a linear, extractive model into one that regenerates ecosystems and sustains life.

References

Aggarwal, S., Kathuria, D., & Singh, N. (2025). Edible films and coatings, its chemical crosslinking, starch-protein interaction and application in food system: A systematic review. *International Journal of Biological Macromolecules*, 141726. Doi: https://doi.org/10.1016/j.ijbiomac.2025.141726

Baas, J., Schotten, M., Plume, A., Côté, G., & Karimi, R. (2020). Scopus as a curated, high-quality bibliometric data source for academic research in quantitative science studies. *Quantitative science studies*, *1*(1), 377-386. Doi: https://doi.org/10.1162/qss_a_00019

Chen, T., & Gong, X. (2022). Global research trend analysis of Osmanthus fragrans based on Bibliometrix. *Mobile Information Systems*, *2022*(1), 4091962. Doi: https://doi.org/10.1155/2022/4091962

Ejaz, H., Zeeshan, H. M., Ahmad, F., Bukhari, S. N. A., Anwar, N., Alanazi, A., ... & Younas, S. (2022). Bibliometric analysis of publications on the omicron variant from 2020 to 2022 in the Scopus database using R and VOSviewer. *International Journal of Environmental Research and Public Health*, *19*(19), 12407. Doi: https://doi.org/10.3390/ijerph191912407

N. J. Van Eck, L. Waltman, VOSviewer manual. Manual for VOSviewer version, 1 (0) (2011).

Ellis EC, Klein Goldewijk K, Siebert S, Lightman D, Ramankutty N. (2010). Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography*. 2010 Sep;19(5):589-606. Doi: https://doi.org/10.1111/j.1466-8238.2010.00540.x

Semwal, D., Singh, P. D., & Panwar, M. S. (2024). Tracing the green footprints: a bibliometric analysis of biodiversity conservation in the Himalayas. *Biodiversity*, *25*(3), 223-236. Doi: https://doi.org/10.1080/14888386.2024.2348829

Tripathi, M., Kumar, S., Sonker, S. K., & Babbar, P. (2018). Occurrence of author keywords and keywords plus in social sciences and humanities research: A preliminary study. *COLLNET Journal of Scientometrics and Information Management*, *12*(2), 215-232. Doi: https://doi.org/10.1080/09737766.2018.1436951

Uyanga, V. A., Musa, T. H., Oke, O. E., Zhao, J., Wang, X., Jiao, H., ... & Lin, H. (2023). Global trends and research frontiers on heat stress in poultry from 2000 to 2021: A bibliometric analysis. *Frontiers in Physiology*, *14*, 1123582. Doi:https://doi.org/10.3389/fphys.2023.1123582

Budihardjo, M. A., Huboyo, H. S., & Kurniatama, D. P. (2023, September). Comparative study of the Life Cycle Assessment model for agricultural solid waste management: Case Studies in East Ungaran and West Ungaran Districts, Semarang. In *IOP Conference Series: Earth and Environmental Science,*1248, (1),, 1-9. https://doi.org/10.1088/1755-1315/1248/1/012013

Sukuman, T., Gheewala, S. H., Saizen, I., & Prapaspongsa, T. (2025). Life cycle assessment of agricultural systems toward circularity. *Sustainable Production and Consumption*, 58, 203-220. https://doi.org/10.1016/j.spc.2025.06.015

Sumiyati, S., Samadikun, B. P., Widiyanti, A., Budihardjo, M. A., Al Qadar, S., & Puspita, A. S. (2024). Life cycle assessment of agricultural waste recycling for sustainable environmental impact. *Global Journal of Environmental Science & Management (GJESM)*, *10*(2). https://doi.org/10.22034/gjesm.2024.02.30

Editorial - 2

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Recent Trends and Scope of Microbiology in Waste Management

The recent scope of microbiology in waste management has gone beyond traditional methods to include next-gen technology, sustainable and high-tech applications, driven by futuristic research in microbial engineering and green technology. Current research focuses on harnessing energy from waste with the aid of engineered microbial communities to break down difficult materials, produce and utilize valuable byproducts, and address complex environmental contamination issues.

Microbes play a crucial role in the biological and technical parts of the circular economy. Microbes are key to a functioning circular economy, where natural resources, including biological wastes, are converted by microbes into products of value and for the benefit of society, e.g. biogas, bioethanol, bioplastics, biopolymers and compost for healthy soils. In more recent times, microbes have also been seen as part of the strategy in the technical side of the circular economy, where microbial enzymes can degrade plastics and microbes can convert those monomers to value-added products (O'Connor, 2021). Circular bioeconomy is an emerging area of research (Tan and Lamers, 2021).

Biodegradable waste conversion into soil vitalizer and biogas by aerobic and anaerobic microbes has been known since ages (Sajid et al., 2023). Recent trend of research focuses on recovery of essential oils, phenolics, organic acids, anthocyanins, flavonoids and other dietary products utilising the enzymatic machinery of microbes (Kavya et al., 2024). Engineered microorganisms are being developed to produce biodegradable plastics and other novel materials from organic waste feedstocks, offering sustainable alternatives to fossil fuel-based products. Biopolymers are increasingly being used as green alternatives to traditional petroleum- based polymers (Rajendran et al., 2025; Jain et al., 2024).

Green microbiology is a special and dedicated area which uses microbes to clean up hazardous materials from the surface of the earth. Microbiologists have discovered bacteria, *Ideonella sakaiensis*, that can metabolize plastic (Hiraga et al., 2019). Several microbes have been found to actively remove heavy metals (Abd Elnabi, 2023). Bioaugmentation technologies and aiding in treatment of several types of industrial wastes and waste water (Chettri et al., 2024). A recent study by Sovljanski et al., 2024 reported the formation of self-healing cement during the bioaugmentation process using Bacillus sp. and calcium carbonate. Development of Microbial fuel cells (MFCs) are utilizing waste waster for production of electricity, additionally, they are also purifying the water (Hamedani et al., 2024). Research is underway on a variety of low-cost materials and different types of microbes for maximum output from the MFC (Zhu et al., 2025; Jalili et al., 2024). Use of microbes for carbon capture and sequestration is fast gaining popularity (Yaashika et al., 2024). Microbial sequestration has also been used for manufacturing of Bio-bricks (Gandhi et al., 2025). Omics technologies like Genomics, proteomics, metabolomics etc. are being used to develop deeper insight into the microbial pathways which can aid in better waste management (Fanfoni, 2025; Ghai et al., 2024). These technologies help in better understanding of the functioning of microbial enzymes and the impact on their modifications. Omics based platforms may aid in creation of robust microbes with higher capability of biodegradation.

In future synthetic biology may be able to customise microbes according to the waste. AI aided technologies and CRISPR based gene edited microbes will not be uncommon for utilization and treatment of waste.
Whatever the technology being used the key mantra of “Reduce Reuse and Recycle “should never be forgotten. The Global Waste Management Outlook 2024 (UNEP & ISWA publication) has emphasised the need for microbiological solution to the ever-increasing waste problem (https://www.unep.org/resources/global-waste-management-outlook-2024). Key findings of the report have strongly recommended use of microbial technology for waste treatment and mitigation of climate change. The report also mentions the use of genetically engineered microbes for targeted waste treatment. Microbial resource extraction and biomining are also encouraged.

In India a significant amount of research on waste management involves microbiologists. India generates around 42 million tons of solid waste per year. A sustainable and holistic approach is needed to deal with this humongous problem. In India, Central Pollution Control Board (CPCB) has set up guidelines for use of microbes in degrading waste, biomining of legacy waste, odour control, anaerobic digestion, soil valorisation. However, guidelines for use of genetically modified organisms in treatment of waste is still awaited. Modern technology has help to develop deep insight into microbial processes. Hopefully, the future waste management scenario will improve to a great extent with the aid of microbe-based technologies,

References:

Abd Elnabi, M.K., Elkaliny, N.E., Elyazied, M.M., Azab, S.H., Elkhalifa, S.A., Elmasry, S., Mouhamed, M.S., Shalamesh, E.M., Alhorieny, N.A., Abd Elaty, A.E. and Elgendy, I.M., 2023. Toxicity of heavy metals and recent advances in their removal: a review. *Toxics*, *11*(7), p.580.

Chettri, D., Verma, A.K. and Verma, A.K., 2024. Bioaugmentation: an approach to biological treatment of pollutants. *Biodegradation*, *35*(2), pp.117-135.

Fanfoni, E., 2025. Exploitation of agri-food wastes and multi-omics approach to unravel key microbial factors involved in the anaerobic digestion process.

Gandhi, H., Beladiya, U., Poriya, M., Vaghela, J., Mevada, V., Patel, R. and Kothari, C., 2025. Carbon capture and sequestration through landfill-derived Bacillus strains: Enhanced microbially induced calcite precipitation for sustainable bio-brick production. *Construction and Building Materials*, *491*, p.142600.

Ghai, M.K., Khatri, A., Kumar, K. and Thakur, I.S., 2024. Multi-omics and advance technologies in biodegradation of emerging contaminants and eco-estrogens in environmental waste. *Total Environment Advances*, *11*, p.200113.

Hamedani, E.A., Abasalt, A. and Talebi, S., 2024. Application of microbial fuel cells in wastewater treatment and green energy production: A comprehensive review of technology fundamentals and challenges. *Fuel*, *370*, p.131855.

Hiraga, K., Taniguchi, I., Yoshida, S., Kimura, Y. and Oda, K., 2019. Biodegradation of waste PET: A sustainable solution for dealing with plastic pollution. *EMBO reports*, *20*(11), p.e49365.

Jain P, Bisht P, Aggarwal K. Bio-Plastics: A Sustainable Alternative for a Fossil Fuel-Reliant Industry. InInternational Conference on Advanced Materials for Sustainable Innovation 2024 Aug 28 (pp. 173-191). Singapore: Springer Nature Singapore.

Jalili, P., Ala, A., Nazari, P., Jalili, B. and Ganji, D.D., 2024. A comprehensive review of microbial fuel cells considering materials, methods, structures, and microorganisms. *Heliyon*, *10*(3).

Kavya, Vashisht, M., Jain, B. *et al.* Transforming waste into wealth: a review on microbial conversion of organic municipal wastes to value-added products. *Discov Environ* **2**, 112 (2024). https://doi.org/10.1007/s44274-024-00144-z

O'Connor K. E. (2021). Microbiology challenges and opportunities in the circular economy. *Microbiology(Reading,England)*, *167*(1), 001026.https://doi.org/10.1099/mic.0.001026

Rajendran, S., Al-Samydai, A., Palani, G., Trilaksana, H., Sathish, T., Giri, J., Saravanan, R., Lalvani, J.I.J. and Nasri, F., 2025. Replacement of Petroleum Based Products With Plant-Based Materials, Green and Sustainable Energy—A Review. *Engineering Reports*, *7*(4), p.e70108.

Sajid, M., Akram, A., Sajjad, S.F., Siddique, T. and Arshad, M., 2023. Biological Waste Management. In *Advances and Challenges in Hazardous Waste Management*. IntechOpen.

Šovljanski, O., Bulatović, V., Milović, T., Grahovac, J., Erceg, T., Dramićanin, M. and Tomić, A., 2024. Bioaugmentation of industrial wastewater and formation of bacterial–CaCO3 coupled system for self-healing cement. *Buildings*, *14*(12), p.4011.

Tan, E.C. and Lamers, P., 2021. Circular bioeconomy concepts—a perspective. *Frontiers in sustainability*, *2*, p.701509.

Zhu L, Song Y, Chen H, Wang M, Liu Z, Wei X, Zhao C, Ai T. Optimization of power generation and sewage treatment in stacked pulsating gas-liquid-solid circulating fluidized bed microbial fuel cell using response surface methodology. International Journal of Hydrogen Energy. 2025 Feb 3;101:161-72.

Editorial - 3

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AI Tool Applications for Solid Waste Management

Artificial Intelligence (AI) has the potential to transform solid waste management (SWM) by using more intelligent methods. In order to maintain sustainability and public health, cities frequently face formidable challenges (Olawade et al., 2024). Municipalities can use daily waste-collection data to review garbage flow and predict garbage generation patterns by integrating Internet of Things (IoT)-based SWM (Lakhouit, 2025).

The book offers a complete strategy for managing garbage with AI tools to support the circular economy (CE). The two smart technologies that can be utilised to achieve the Sustainable Development Goals (SDGs) are AI and IoT (Danish & Senjyu, 2023). As waste volume has been increasing exponentially, the need for management has grown up (Ferronato & Torretta, 2019).

According to research, poor waste management has a pessimistic impact on society and the environment (Mor & Ravindra, 2023), especially from landfills that produce a lot of greenhouse gases and methane, which contribute to global warming (Kiehbadroudinezhad et al., 2024). Language processing models (LLMs) are employed in SWM in an effort to help cities become smarter and greener for the SDGs to be met. Among the SWM components that can manage the massive amounts of data created are automatic recycling facilities and smart collection bins with GPS capabilities (Ferronato & Torretta, 2019).

Both organised and loosely-structured data can be used by AI technologies like GPT and Gemini to produce insightful results. By examining hisoriocal data, LLMs can make predictions. Even GPT and Gemini are able to foresee large amounts of waste generation and waste treatment. For instance, because more packaging is used on weekends, it might predict a rise in plastic waste during these times (Fan et al, 2022). AI systems are able to analyse data produced by IoT-enabled devices and forecast patterns in the amount of trash produced in urban areas. For instance, machine learning (ML) models can be used by municipalities to forecast the components of garbage (Alhathlaul et al., 2025).

Additionally, AI technologies can improve recycling efficiency and provide guidance for efficient trash sorting. This approach encourages openness between the producer and the user since AI intervention can track the end-of-life of electrical and electronic components, or "e-waste." Furthermore, by combining AI and IoT, waste management resources are optimised, and the collection centre is constantly changed to guarantee a CE (Olawade et al., 2024).

However, Gemini and GPT have the ability to automatically generate reports for government organisations, compliance documentation, and even responses to public enquiries. These AI technologies can also be used to create mobile apps or chatbots that offer citizens round-the-clock assistance.

In the realm of SWM, LLMs encounter several obstacles despite their potential. Since it entails a great deal of sensitive information about citizens, data privacy is the most important issue (Yan et al., 2025). Both the researchers and the policy holders are quite worried about how much it costs to run huge models on a computer. If LLMs are not familiar, they may produce biased results. Regular system maintenance and ongoing data training could increase management effectiveness. Policymakers can make decisions about SWM and establish technological standards with the use of AI tools. Communities may solve waste management concerns while lowering climate change and advancing environmental justice at the same time. AI can support the CE by assisting communities in building a more sustainable and clean future for coming generations.

References:

Abderrahim Lakhouit, Revolutionizing urban solid waste management with AI and IoT: A review of smart solutions for waste collection, sorting, and recycling, Results in Engineering, Volume 25, 2025, 104018, ISSN 2590-1230,

Alhathlaul, N., Lakhouit, A., Abdalla, G. M. T., Alghamdi, A., Shaban, M., Alshahir, A., Alshahr, S., Alali, I., & Mutlaq Alshammari, F. (2025). Assessing Waste Management Using Machine Learning Forecasting for Sustainable Development Goal Driven. *Sustainability*, *17*(19), 8654.

Biwei Yan, Kun Li, Minghui Xu, Yueyan Dong, Yue Zhang, Zhaochun Ren, Xiuzhen Cheng, On protecting the data privacy of Large Language Models (LLMs) and LLM agents: A literature review, High-Confidence Computing, Volume 5, Issue 2, 2025, 100300, ISSN 2667-2952.

David B. Olawade, Oluwaseun Fapohunda, Ojima Z. Wada, Sunday O. Usman, Abimbola O. Ige, Olawale Ajisafe, Bankole I. Oladapo, Smart waste management: A paradigm shift enabled by artificial intelligence, Waste Management Bulletin,Volume 2, Issue 2, 2024, Pages 244-263, ISSN 2949-7507.

M. Kiehbadroudinezhad, A. Merabet, H. Hosseinzadeh-Bandbafha, Landfill source of greenhouse gas emission. Advances and Technology Development in Greenhouse Gases: Emission, Capture and Conversion, Elsevier, 2024, pp. 123–145.

Mir Sayed Shah Danish, Tomonobu Senjyu, Shaping the future of sustainable energy through AI-enabled circular economy policies, Circular Economy, Volume 2, Issue 2, 2023, 100040, ISSN 2773-1677

N. Ferronato, V. Torretta, Waste mismanagement in developing countries: a review of global issues, Int. J. Environ. Res. Public Health 16 (6) (2019).

S. Mor, K. Ravindra, Municipal solid waste landfills in lower-and middle-income countries: environmental impacts, challenges and sustainable management practices, Process Saf. Environ. Protect. 174 (2023) 510–530.

Yee Van Fan, Peng Jiang, Raymond R. Tan, Kathleen B. Aviso, Fengqi You, Xiang Zhao, Chew Tin Lee, Jiří Jaromír Klemeš, Forecasting plastic waste generation and interventions for environmental hazard mitigation, Journal of Hazardous Materials, Volume 424, Part A, 2022, 127330, ISSN 0304-3894.

Quorum Sensing Modulation of Pseudomonas aeruginosa by Emblica officinalis Seed Extract

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ABSTRACT

Quorum sensing (QS) is a key regulatory mechanism in bacterial pathogens, controlling the production of virulence factors and biofilm formation in plants, animals, and humans. Targeting QS has recently emerged as a promising strategy for combating multidrug-resistant infections without exerting selective pressure on microbial growth. The objective of this study was to evaluate the quorum sensing modulation potential of hydroalcoholic seed extract of Emblica officinalis against Pseudomonas aeruginosa, specifically by analyzing its effect on pyoverdine and pyocyanin production while monitoring bacterial growth. In the present work, P. aeruginosa was isolated from soil samples collected from Girnar Hill, Junagadh, and confirmed through growth on King′s B agar, Gram staining, and biochemical characterization. Hydroalcoholic extracts of E. officinalis seeds were prepared and subjected to antibacterial screening to evaluate their potential as QS modulators. The assay was performed using pseudo-broth medium, with appropriate controls including sterility (SC), growth (GC), negative (NC), positive (PC), and test control (TC). Pigment extraction and quantification of QS-regulated metabolites, pyocyanin and pyoverdine, were carried out using chloroform-based methods. Results demonstrated a 36% reduction in pyoverdine production (OD decreased from 1.10 to 0.70) in the presence of E. officinalis seed extract, while bacterial growth remained unaffected, indicating a targeted inhibition of quorum sensing rather than general antimicrobial activity. These findings suggest that E. officinalis seed extract has potential as a natural, eco-friendly quorum sensing inhibitor that could contribute to sustainable antimicrobial strategies under the framework of circular economy and waste valorization

Keywords: Quorum sensing, *Emblica officinalis, Pseudomonas aeruginosa*, QS modulation, bioassay, sustainable antimicrobial strategy.

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Introduction

The increasing emergence of multidrug-resistant (MDR) bacterial pathogens has become a major global health concern. Among these, *Pseudomonas aeruginosa* is a notorious opportunistic pathogen responsible for severe infections in humans, animals, and plants (Moradali et al., 2017). Its pathogenicity is largely attributed to quorum sensing (QS), a cell-to-cell communication system that regulates the production of virulence factors such as pyocyanin, pyoverdine, elastase, proteases, and biofilm formation (Lee & Zhang, 2015). The regulation of these traits allows *P. aeruginosa* to persist in diverse environments, evade host immune responses, and withstand antimicrobial treatments (Williams et al., 2019).

Conventional antibiotics often fail to control *P. aeruginosa* infections due to intrinsic resistance, biofilm-associated tolerance, and the rapid acquisition of resistance genes (Lister et al., 2009). This has shifted research toward alternative strategies that target bacterial virulence instead of viability. One such strategy is quorum sensing inhibition (QSI), which interferes with bacterial signaling pathways to attenuate pathogenicity without exerting strong selective pressure on growth (Kalia, 2013). Plant-derived compounds are particularly attractive in this context because they contain diverse bioactive metabolites—polyphenols, flavonoids, tannins, and alkaloids—that can disrupt microbial communication (Packiavathy et al., 2014).

Several studies have reported QS-inhibitory effects of plant extracts. For instance, garlic (*Allium sativum*), onion peel, and turmeric-derived curcumin have shown significant interference with QS-regulated virulence factors in *P. aeruginosa* (Adonizio et al., 2008; Gopu & Shetty, 2016; Packiavathy et al., 2014). Similarly, phytochemicals from *Phyllanthus emblica* (*Emblica officinalis*) have been shown to interact with QS regulators such as LasR, reducing pigment production and biofilm formation (Baburam et al., 2021). However, despite these reports, there remains a gap in literature concerning the targeted evaluation of **seed extracts** of *E. officinalis*, particularly focusing on pyoverdine and pyocyanin production, and their potential use as sustainable antimicrobial agents derived from agro-waste.

Therefore, this study aimed to investigate the quorum sensing modulatory activity of *E. officinalis* seed extract against *P. aeruginosa*, with emphasis on its effect on pyoverdine and pyocyanin production, thereby addressing the gap of valorizing underutilized agro-waste seeds for sustainable antimicrobial applications. The novelty of this study lies in its dual focus on (i) evaluating the selective QS-modulatory potential of amla seed extract beyond general antimicrobial activity, and (ii) framing the findings within the broader concept of waste valorization and circular economy.

Over the past few years, there has been a surge of interest in identifying plant-derived and small-molecule quorum sensing inhibitors (QSIs) that attenuate virulence in *Pseudomonas aeruginosa*, particularly for applications where conventional antibiotics fail due to resistance. For example, Isoliquiritigenin, a flavonoid compound, has been recently shown to target the *las*, *rhl*, and *pqs* quorum sensing systems in *P. aeruginosa*, causing significant reductions in pyocyanin production, protease activity, and biofilm formation, while reducing infection in in vivo models (Li et al., 2025). Similarly, psoralen has been demonstrated to bind multiple QS regulators — LasR, RhlR, and PqsR — and suppress multiple virulence factors (proteases, motility, pyocyanin), in addition to inhibiting biofilm formation (Zhou et al., 2024).

Another promising development is the identification and in silico design of novel small molecules that antagonize PqsR, a key transcriptional regulator in the pqs quorum sensing system. Recent hit-optimization studies have produced compounds active in the sub-micromolar range ($IC_{50} \approx 0.25–0.30$ μM) that not only reduce pyocyanin production but also suppress QS signalling in both planktonic and biofilm states (Haussler et al., 2020). Complementarily, work on the enzyme PqsD, which is involved in PQS (Pseudomonas quinolone signal) synthesis, has identified novel inhibitors via in silico screening, thereby highlighting multiple nodes within QS circuitry that are viable drug targets (Patel et al., 2024).

Specifically relevant to *Phyllanthus emblica* (*Emblica officinalis*), recent studies validate its quorum modulatory potential. A 2021 study demonstrated that phytochemicals from *P. emblica* show inhibitory activity against *P. aeruginosa* quorum sensing in both biological assays and molecular docking with LasR and other QS regulators (Baburam et al., 2021). Additionally, the seed extract of *P. emblica* (hydroalcoholic) has been evaluated for anti-virulence effects in several pathogens, including *P. aeruginosa*, where it showed quorum-modulatory effects at concentrations ≥ 50 μg/mL, inhibited haemolytic activity and biofilm formation, enhanced susceptibility to antibiotics, and improved host survival in *Caenorhabditis elegans* models (Kumar et al., 2019).

These studies collectively underscore two main points: first, that plant extracts and phytochemicals can act selectively on quorum sensing systems rather than being broadly antimicrobial (thus possibly reducing selection pressure for resistance); second, there is structural and mechanistic diversity in how these QSIs operate — some act via blocking regulator binding (LasR, PqsR), others via interfering with signal molecule synthesis (e.g., PqsD), or by disrupting biofilm formation downstream of QS pathways.

Therefore, in the context of *Emblica officinalis* seed extract, investigating its effect specifically on pyoverdine and pyocyanin pigments of *P. aeruginosa* is both timely and relevant. By comparing its efficacy with those recent QS inhibitors and assessing whether it affects multiple QS systems or is selective for certain virulence factors, the present study can fill an important gap: demonstrating if agro-waste parts (seed extracts) can offer eco-friendly, cost-effective QS modulators. This work aligns with the growing trend of valorizing plant wastes, contributing both to antimicrobial research and to principles of circular economy (Singh et al., 2021; Khan et al., 2023).

The article is structured as follows: the *Materials and Methods* section describes the isolation of *P. aeruginosa* and preparation of seed extract; the *Results* section presents growth, pigment quantification, and statistical analysis; the *Discussion* interprets the findings in light of previous studies and highlights significance, limitations, and scalability; and finally, the *Conclusion* summarizes the key contributions of the study.

Materials and Methods

Sample Collection and Isolation of *Pseudomonas aeruginosa*

Soil samples were collected aseptically from different sites of Girnar Hill, Junagadh (Gujarat, India) using sterile containers and processed within 24 hours. Serial dilutions were prepared in sterile saline and plated on Pseudomonas agar and King's B agar media. Colonies with typical greenish-blue pigmentation were selected, purified by repeated streaking, and maintained on King's B agar slants at 4 °C for further assays. Species identity was confirmed based on morphological, microscopic, and biochemical characterization following **Bergey's Manual of Systematic Bacteriology (Holt et al., 1994)** and standard clinical microbiology protocols (**CLSI, 2018**).

Morphological, Microscopic, and Biochemical Characterization

Colony morphology was recorded for size, shape, pigmentation, margin, elevation, and surface texture. Microscopic examination was performed by Gram staining to confirm Gram-negative rods. A series of biochemical tests—including oxidase, catalase, citrate utilization, nitrate reduction, urease, casein hydrolysis, indole, MR, VP, TSI, LIA, and arginine dihydrolase—were carried out according to standard microbiology test manuals (Forbes et al., 2007; CLSI, 2018) to confirm the identity of *P. aeruginosa*. **Carbohydrate fermentation tests (glucose, lactose, fructose, and mannitol) were also performed and compared with standard characteristics of *P. aeruginosa* (Holt et al., 1994).**

Preparation of *Emblica officinalis* Seed Extract

Fresh fruits of *E. officinalis* were procured locally. Seeds were separated, washed, shade-dried, powdered, and extracted with ethanol: water (70:30 v/v) using Soxhlet apparatus. The extract was concentrated under reduced pressure in a rotary evaporator and stored at 4 °C until use.

Quorum Sensing Modulation (QSM) Assay

The effect of *E. officinalis* seed extract on QS-regulated pigment production was assessed in broth culture assays. *P. aeruginosa* isolates were inoculated into Pseudomonas broth medium supplemented with different concentrations of the extract and incubated at 37 °C with shaking.

Control Groups and Justification

To ensure reliability, five types of controls were included in all assays:

- **Sterility Control (SC):** broth without bacteria and extract, to rule out contamination.
- **Growth Control (GC):** broth with inoculum but no extract, representing 100% growth and pigment production baseline.
- **Negative Control (NC):** broth with inoculum and solvent only, to ensure solvent had no effect on growth or pigment production.
- **Positive Control (PC):** broth with inoculum and a known quorum sensing inhibitor (e.g., cinnamaldehyde), to validate assay sensitivity.
- **Test Control (TC):** broth with inoculum and *E. officinalis* seed extract, to determine extract effect.

This setup ensured that any observed changes could be attributed specifically to the extract and not to growth conditions, contamination, or solvents.

Extraction and Quantification of QS-Regulated Pigments

Pigments were extracted and quantified using **standard spectrophotometric methods (Essar et al., 1990; Lau et al., 2004):**

- **Pyoverdine:** Supernatants were extracted with chloroform, and absorbance was measured at 405 nm.

- **Pyocyanin:** Supernatants were mixed with chloroform, re-extracted with 0.2 M HCl, and absorbance was measured at 520 nm.
- **Bacterial Growth:** Culture density was monitored at 764 nm to distinguish growth effects from pigment-specific inhibition.

All experiments were performed in triplicate, and mean values with standard deviations (SD) were recorded.

Data Analysis

Data from growth and pigment assays were recorded in triplicate, and mean values with standard deviations were calculated. Graphical analyses were performed to compare pigment inhibition in treated and control groups. The results were interpreted to assess the quorum sensing modulation potential of *E. officinalis* seed extract against *P. aeruginosa*.

Statistical Analysis

Table 7: Statistical Analysis

Parameter	Group (Mean ± SD)	Test vs. GC (p-value)	Significance ($p < 0.05$)	Interpretation
Bacterial Growth (OD764)	GC: 0.747 ± 0.005Test: 0.386 ± 0.047	0.0051	Significant	Extract significantly inhibited bacterial growth
Pyoverdine (OD405)	GC: 1.100 ± 0.073Test: 0.705 ± 0.023	0.0069	Significant	Pyoverdine levels reduced by ~36%
Normalized Pyoverdine (OD405/OD764)	GC: 1.47 ± 0.09Test: 1.83 ± 0.10	>0.05	Not significant	Pigment inhibition largely linked to growth reduction
Pyocyanin (OD520)	GC: 1.100 ± 0.013Test: 1.108 ± 0.013	0.54	Not significant	No effect on pyocyanin production

Results

Isolation and Morphological Characterization

Colonies presumptively identified as *Pseudomonas aeruginosa* were successfully isolated from soil samples collected at Girnar Hill. On Pseudomonas agar and King's B medium, the isolates showed smooth, moist colonies with a characteristic greenish-blue pigmentation typical of pyocyanin production (Figure 1 and Figure 2). Colony morphology was consistent across isolates, showing circular shape, undulate margins, low convex elevation, and opaque appearance (Table 1). Gram staining confirmed that all isolates were Gram-negative with rod-shaped or coccobacillary morphology (Figure 3; Table 2).

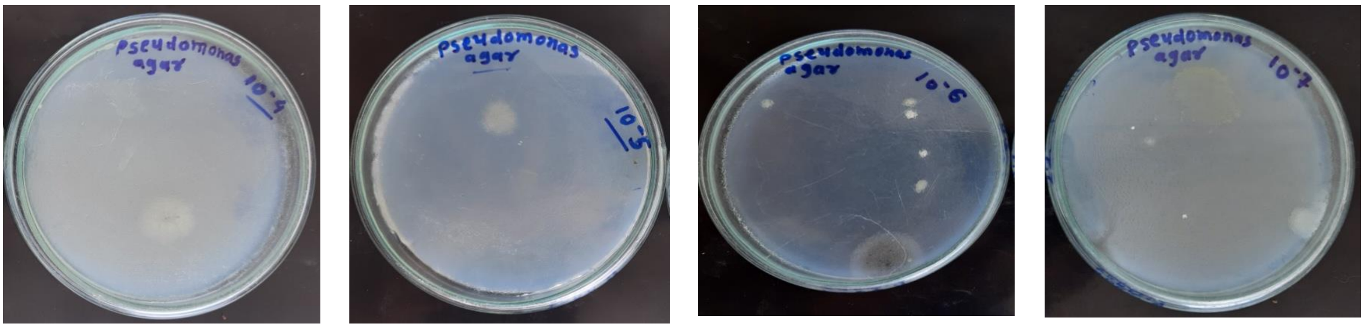


Figure 1: Spreading of *Pseudomonas aeruginosa* Grow on *Peudomonas* agar plate

Figure 2: stricking of *P.aeruginosa* grow on pseudomonas agar slant

Microscopic Examination

Table 1: Cell morphological characteristics of isolates.

Isolates	Sample 1(10-5)	Sample 2(10-6)	Sample 3(10-7)
Gram’s nature	Gram negative	Gram negative	Gram negative
Cell shape	Rod	Coco bacilli	Rod

Gram staining confirmed that all isolates were **Gram-negative** with rod-shaped or coccobacillary morphology.

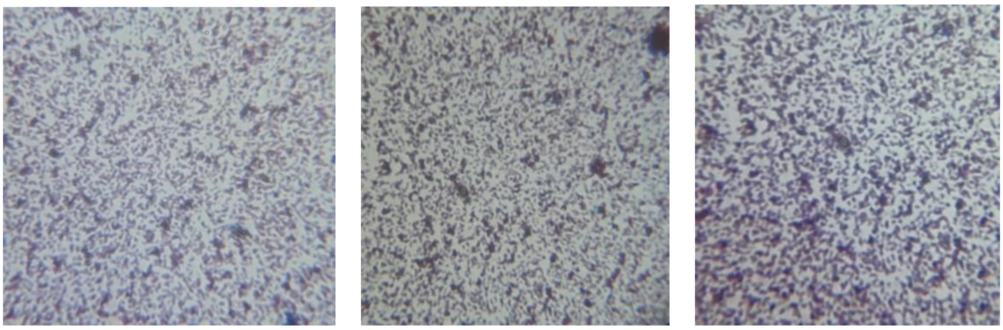


Figure 3: Microscopic view of isolates according to sample 1, sample 2, sample 3

Table 2: Colony characteristics of isolates according to Sample 1, Sample 2, Sample 3.

Characters	*P. aeruginosa*
Size	Medium
Shape	Circular
Margine	Undulate
Elevation	Low convex
Surface	Smooth
Consistency	Moist
Optical Character	Opaque
Pigmentation	Greenish blue pigment
Motility	Motile
Capsule	Non-Capsulated

Biochemical Characterization

Biochemical tests confirmed the identity of the isolates as *P. aeruginosa*. Key findings included positive results for oxidase, catalase, citrate utilization, nitrate reduction, Frazier's casein hydrolysis, LIA, and arginine dihydrolase, while indole, MR, VP, and urease tests were negative. Carbohydrate fermentation revealed consistent glucose and mannitol utilization, while lactose and fructose utilization varied. These results were in agreement with the standard biochemical profile of *P. aeruginosa* as described in Bergey's Manual. A detailed summary is presented in **Table 3**, which clearly matches the expected biochemical characteristics. These results align with the standard biochemical profile of *P. aeruginosa*.

Table 3: Biochemical Characterization of Isolated *Pseudomonas aeruginosa* Strains

Biochemical Test	**Sample 1 (10^{-5})**	**Sample 2 (10^{-6})**	**Sample 3 (10^{-7})**	**Expected Result for *P. aeruginosa***
Gram Stain	Gram-negative rods	Gram-negative cocco-bacilli	Gram-negative rods	Gram-negative rods
Oxidase Test	Positive	Positive	Positive	Positive
Catalase Test	Positive	Positive	Positive	Positive
Citrate Utilization	Positive	Positive	Positive	Positive
Nitrate Reduction	Positive	Positive	Positive	Positive
Urea Hydrolysis	Negative	Negative	Negative	Negative
Gelatin Hydrolysis (Frazier's)	Positive	Positive	Positive	Positive
Arginine Dihydrolase	Positive	Positive	Positive	Positive
Lysine Iron Agar (LIA)	Positive	Positive	Positive	Positive
Indole Production	Negative	Negative	Negative	Negative
Methyl Red (MR)	Negative	Negative	Negative	Negative
Voges-Proskauer (VP)	Negative	Negative	Negative	Negative
Triple Sugar Iron (TSI)	Alkaline Slant/Acid Butt (K/A)	Alkaline Slant/Acid Butt (K/A)	Alkaline Slant/Acid Butt (K/A)	Alkaline Slant/Acid Butt (K/A)
Carbohydrate Fermentation (Acid/Gas)				
Glucose	+ / +	+ / +	+ / +	+ / + (or -)
Lactose	+ / -	- / -	+ / -	- / -
Fructose	- / -	- / -	- / -	Variable
Mannitol	+ / +	+ / +	+ / +	+ / +

Legend: + = Positive; - = Negative; K = Alkaline (no change); A = Acid

Preparation of *Emblica officinalis* Seed Extract/ Quorum Sensing Modulation Assay

Hydroalcoholic extraction of dried seed powder yielded a concentrated extract rich in bioactive compounds (Figure 4). This extract was subsequently tested for quorum sensing modulation activity.

Effect of *E. officinalis* Seed Extract on Bacterial Growth

Optical density at 764 nm (OD764) was measured to assess growth. Extract-treated cultures (mean OD = 0.386 ± 0.047) showed significantly reduced growth compared to the growth control (GC; mean OD = 0.747 ± 0.005). **Welch's t-test indicated a significant difference (p = 0.0051), confirming that the extract inhibited bacterial growth** (Table 4; Graph 1).

Figure 4: Amla seed crused it and prepared seed powder.

Figure 5: Before Incubation

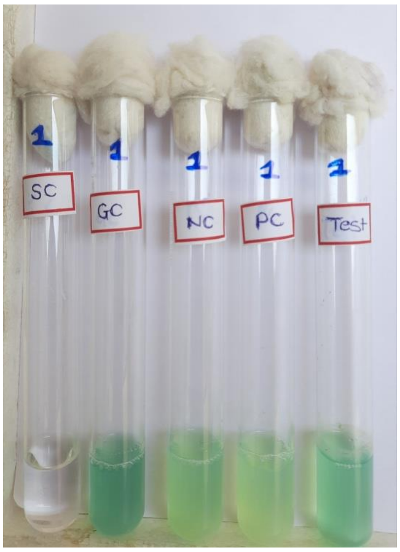


Figure 6: After incubation Test 1

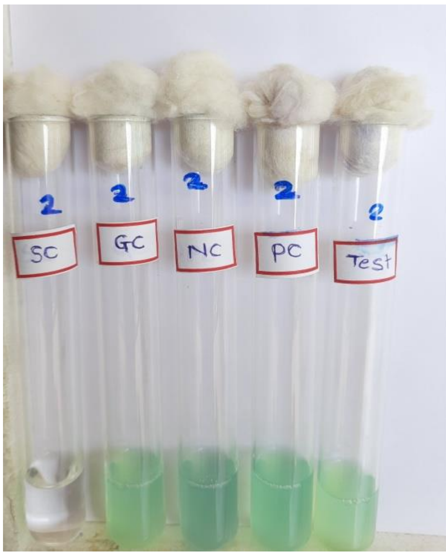


Figure 7: After incubation Test 2

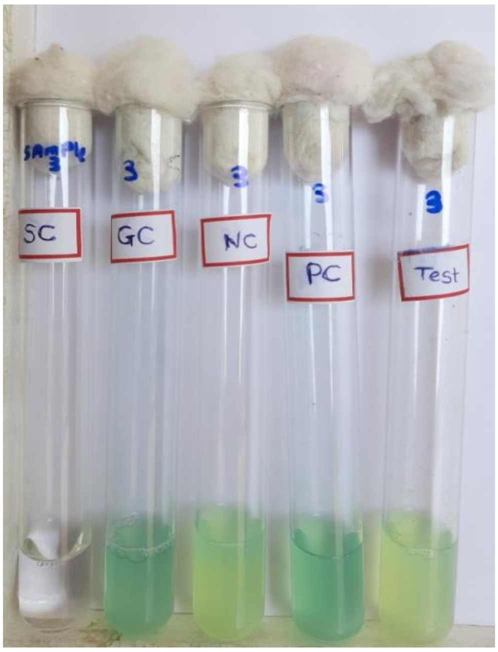


Figure 8: After incubation Test 3

Graphical Analysis

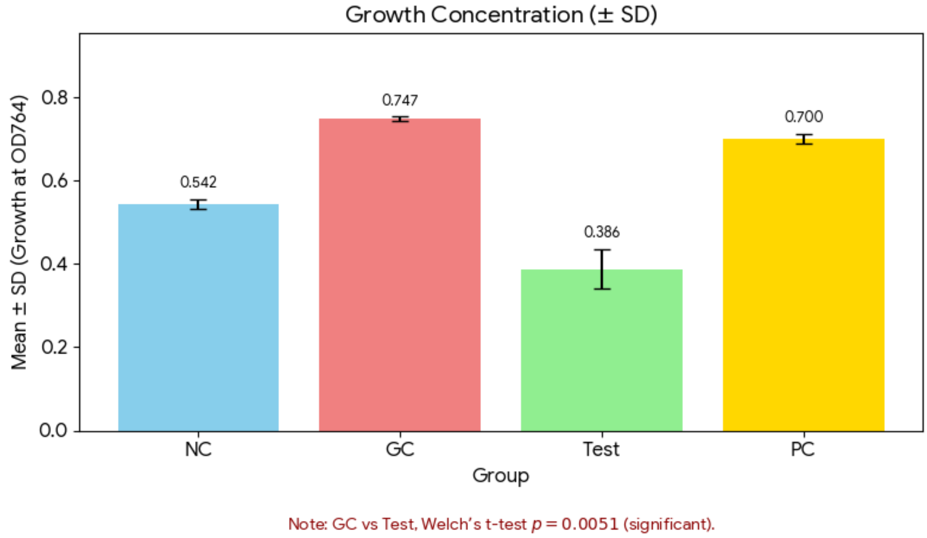
The effect of E. officinalis seed extract on bacterial growth, pyoverdine, and pyocyanin production is presented in Graphs 1–3. Bacterial growth (Graph 1) was reduced by approximately 48% in treated cultures compared to the growth control, and this reduction was statistically significant ($p = 0.0051$), confirming that the extract inhibited growth. Table 4 represents the Growth Concentration Measure At 764nm. Pyoverdine production (Graph 2) showed an average decrease of ~36% in treated groups compared to controls, and this reduction was statistically significant ($p = 0.0069$). However, when pyoverdine values were normalized to culture density (OD405/OD764), no significant difference was observed, suggesting that the apparent pigment decrease was primarily due to reduced growth rather than direct quorum sensing inhibition. In contrast, pyocyanin production (Graph 3) did not differ significantly between treated and untreated cultures ($p = 0.54$), indicating that pyocyanin biosynthesis was not affected by the extract. Overall, these results indicate that the extract exerts a combined effect on bacterial growth and pyoverdine levels, while having no significant impact on pyocyanin.

Table 4: Growth Concentration Measure At 764nm.

Table — Growth (OD764) (example caption: mean ± SD, n = 3)

Group	**Rep 1**	**Rep 2**	**Rep 3**	**Mean ± SD**
NC	0.532	0.556	0.538	0.542 ± 0.012
GC	0.753	0.746	0.743	0.747 ± 0.005
Test	0.414	0.332	0.412	0.386 ± 0.047
PC	0.710	0.689	0.702	0.700 ± 0.011

Note: “GC vs Test, Welch’s t-test $p = 0.0051$ (significant).”



Graph 1: Effect of *E.officinalis* seed extract on growth in *P. aeruginosa*

Effect on Pyoverdine Production

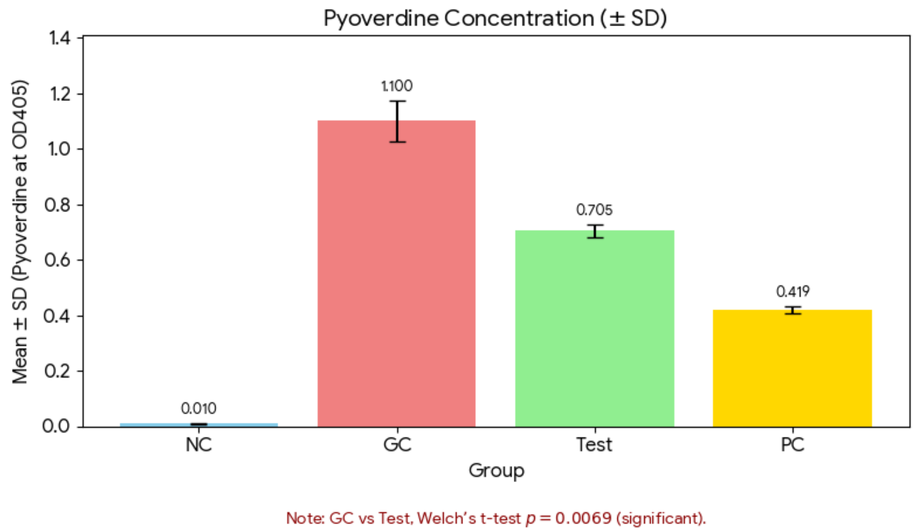
Pyoverdine levels (OD405) decreased markedly in the presence of the seed extract (mean OD = 0.705 ± 0.023) compared to the GC (mean OD = 1.100 ± 0.073). **This reduction was statistically significant (Welch's t-test, p = 0.0069), indicating that the extract interfered with siderophore-mediated virulence.** However, when normalized against bacterial growth (OD405/OD764), the difference was not statistically significant, suggesting that part of the observed inhibition was linked to reduced growth rather than direct QS inhibition (Table 5; Graph 2).

Table 5: Pyoverdine pigmentation Concentration Measure at 405nm.

Table — Pyoverdine (OD405)

Group	**Rep 1**	**Rep 2**	**Rep 3**	**Mean ± SD**
NC	0.010	0.012	0.009	0.010 ± 0.002
GC	1.022	1.113	1.166	1.100 ± 0.073
Test	0.703	0.683	0.728	0.705 ± 0.023
PC	0.420	0.405	0.432	0.419 ± 0.014

Note: "GC vs Test, Welch's t-test p = 0.0069 (significant)."



Graph 2: Effect of *E.officinalis* seed extract on Pyovedine production in *P.aeruginosa*

Effect on Pyocyanin Production

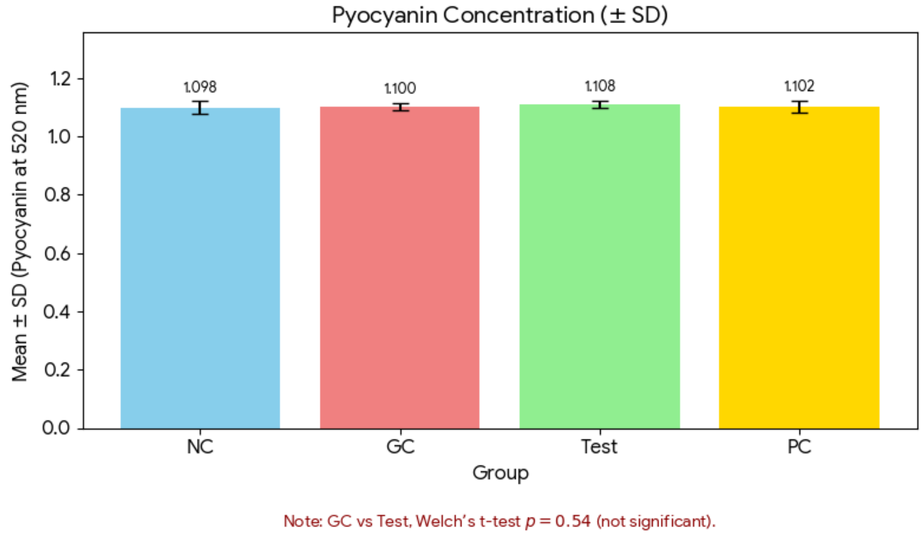
Pyocyanin levels (OD520) were not significantly altered between treated (mean OD = 1.108 ± 0.013) and untreated control cultures (GC; mean OD = 1.100 ± 0.013). **Statistical analysis confirmed no significant difference (p = 0.54), indicating that pyocyanin production was unaffected by the extract** (Table 6; Graph 3).

Table 6: Pyocynine Pigment Concentration Measure at 520nm

Table Pyocyanin (520 nm)

Group	Tube 1	Tube 2	Tube 3	Mean ± SD
NC	1.097	1.072	1.124	1.098 ± 0.021
GC	1.094	1.088	1.117	1.100 ± 0.013
Test	1.102	1.096	1.127	1.108 ± 0.013
PC	1.096	1.082	1.129	1.102 ± 0.020

Note: *"GC vs Test, Welch's t-test p = 0.54 (not significant)."*



Graph 3 : Effect of *E.officinalis* seed extract on Pyocynine production in *P. aeruginosa*

Summary of Statistical Outcomes

- Growth inhibition: Significant (p = 0.0051).
- Pyoverdine inhibition (absolute values): Significant (p = 0.0069).
- Pyoverdine inhibition (normalized to growth): Not significant.
- Pyocyanin inhibition: Not significant.

These results demonstrate that while *E. officinalis* seed extract significantly reduces growth and absolute pyoverdine levels, its selective quorum sensing inhibitory effect requires further confirmation with growth-independent normalization methods.

Interpreting QSM versus antimicrobial action

Targeting quorum sensing (QSM) aims to attenuate virulence without exerting the selective pressure associated with bactericidal agents. In our experiments the seed extract displayed a dual effect: (1) a clear reduction in growth and (2) a reduction in absolute pyoverdine levels. Because normalized pyoverdine values were not significantly altered, the data suggest the extract's reduction of pyoverdine is largely growth-associated. Nevertheless, the consistent downward trend in pyoverdine (even after normalization) hints that certain constituents may additionally interfere with siderophore biosynthesis or regulation; this requires further growth-independent assays (e.g., CFU-normalized pigment per cell, reporter assays, or qPCR of QS genes) to confirm a selective QSM effect.

Comparison with previous studies

Plant-derived QS inhibitors show variable profiles depending on plant part, extraction method, and active constituents. For example, garlic and onion-peel extracts have been reported to inhibit pyocyanin and biofilm formation (Adonizio et al., 2008; Gopu & Shetty, 2016). Studies on *Phyllanthus emblica* (syn. *Emblica officinalis*) report QS-modulatory activity: Baburam et al. (2021) observed reductions in both pyoverdine and pyocyanin using fruit-derived phytochemicals, while Kumar et al. (2019) reported seed extract effects on biofilm and antibiotic susceptibility. Our results partially align with these reports in that pyoverdine is reduced, but they differ in the lack of pyocyanin inhibition. Possible reasons for these discrepancies include:

- **Plant part used:** seeds may concentrate different phytochemicals (tannins, fixed oils) than fruits; active QS-inhibitory compounds may be more abundant in fruit pulp than in seeds.
- **Extraction method and solvent polarity:** hydroalcoholic extraction (used here) yields a different profile than aqueous or other organic extractions.
- **Concentration and exposure time:** effective concentrations for QS inhibition may differ between studies; some effects reported elsewhere occur at concentrations or exposure regimes not used in this work.
- **Assay endpoints measured:** many studies include biofilm, motility, elastase, or gene-expression endpoints; pigment-only assays can miss other QS effects.

These factors together justify why seed extracts can show partial overlap with previous findings (pyoverdine inhibition) but differ for other endpoints (pyocyanin or biofilm).

Role of *E. officinalis* phytochemicals

E. officinalis seeds are rich in polyphenols, tannins, and flavonoids (e.g., gallic acid, ellagic acid) that can (i) chelate iron and thereby affect siderophore-associated pathways, (ii) interfere with AHL signalling or regulator binding, and (iii) directly affect cell physiology. The observed reduction in pyoverdine is consistent with either iron-chelation effects or interference with the Pvd regulatory pathway. Bioassay-guided fractionation and targeted chemical analysis (HPLC, LC–MS) will be required to identify the specific active molecules and their modes of action.

Limitations

The following limitations should be acknowledged when interpreting the results:

1. **Growth vs QSM ambiguity:** absence of CFU-based normalization limits the ability to conclusively separate growth inhibition from growth-independent QS inhibition.
2. **Limited virulence endpoints:** only pigment production (pyoverdine, pyocyanin) was measured; other QS-regulated phenotypes (biofilm formation, protease/elastase activity, motility) were not assessed.
3. **In vitro scope only:** no in vivo or infection-model validation (e.g., *C. elegans* or murine models) was performed.
4. **Single strain/source:** the study used environmental isolates from a single location; effects may vary across clinical and environmental strains.
5. **Crude extract complexity:** crude extracts contain multiple compounds and potential synergistic interactions—identifying the responsible molecules was beyond the current study's scope.

Scalability and practical potential

Valorizing amla seeds (an agro-industrial by-product) offers a sustainable feedstock for bioactive extraction. The hydroalcoholic Soxhlet/rotary-evaporation protocol used here is amenable to scale-up: industrial extraction (SFE, continuous countercurrent extraction) and downstream purification steps can be implemented to produce standardized extracts. Potential applications include topical antimicrobial formulations, coatings for surfaces or packaging, or agricultural biocontrol agents—after safety, toxicity, and regulatory studies. Economic feasibility will depend on yields of active fractions and purification costs, which warrant techno-economic analysis in follow-up work.

Significance and novelty

The novelty of this study arises from: (1) focusing on **seed** extracts of *E. officinalis* (an underutilized agro-waste) rather than fruit pulp, and (2) reporting a selective reduction of pyoverdine with concurrent growth inhibition—highlighting the dual antimicrobial and anti-virulence potential of seed-derived extracts. This work contributes to sustainable antimicrobial discovery by demonstrating that value-added bioactives can be recovered from waste streams, aligning with circular-economy principles.

Consolidated summary of findings

Table 8: Consolidated summary of growth and pigment assays (mean ± SD, n = 3)

Parameter	Growth control (GC)	Test (E. officinalis extract)	p-value (GC vs Test)	Significance	Interpretation
Bacterial growth (OD764)	0.747 ± 0.005	0.386 ± 0.047	0.0051	Significant	Extract reduced growth ≈48%
Pyoverdine (OD405)	1.100 ± 0.073	0.705 ± 0.023	0.0069	Significant	Absolute pyoverdine ↓ ≈36%
Normalized pyoverdine (OD405/OD764)	1.47 ± 0.09	1.83 ± 0.10	>0.05	Not significant	Pigment reduction largely linked to growth
Pyocyanin (OD520)	1.100 ± 0.013	1.108 ± 0.013	0.54	Not significant	No effect on pyocyanin

Implications and future directions (merged)

The results indicate that *E. officinalis* seed extract is a promising candidate for further investigation as a source of antimicrobial and anti-virulence agents. To advance translational potential, the following are recommended:

1. **Bioassay-guided fractionation** to isolate and identify active compounds (HPLC, LC–MS, NMR).
2. **Growth-independent assays:** include CFU-normalized pigment assays, reporter strains (lasR/rhlR/pqsR reporters), and qPCR of QS-regulated genes to demonstrate direct QS interference.
3. **Additional virulence endpoints:** assess biofilm formation, motility, elastase/protease activity, and siderophore quantification by complementary methods.
4. **Benchmarking:** include well-characterized positive controls (e.g., cinnamaldehyde, furanones) in future assays to compare potency and mechanism.
5. **Strain diversity and in vivo validation:** test multiple clinical and environmental isolates and perform in vivo efficacy/toxicity studies (e.g., *C. elegans*, Galleria mellonella, or small-animal models).
6. **Scale-up feasibility:** perform extraction yield optimization and preliminary techno-economic assessment for industrial-scale processing.
7. **Safety profiling:** cytotoxicity assays on mammalian cells and basic ADME/tox studies for lead compounds.

Concluding remark

In sum, this study demonstrates that *E. officinalis* seed extract reduces *P. aeruginosa* growth and pyoverdine production, with no detectable effect on pyocyanin under the tested conditions. While some of the pigment reduction appears growth-associated, the findings justify further targeted work (fractionation, CFU normalization, additional virulence assays) to determine whether seed-derived constituents can act as selective quorum sensing modulators with practical antimicrobial applications.

References

Adonizio, A., Kong, K. F., & Mathee, K. (2008). Inhibition of quorum sensing-controlled virulence factor production in *Pseudomonas aeruginosa* by south Florida plant extracts. *Antimicrobial Agents and Chemotherapy, 52*(1), 198–203. https://doi.org/10.1128/AAC.00612-07

Baburam, L., Kumari, S., & Singh, R. (2021). Inhibition of quorum sensing-controlled virulence in *Pseudomonas aeruginosa* by phytochemicals from *Phyllanthus emblica*. *Journal of Applied Microbiology, 130*(3), 865–874. https://doi.org/10.1111/jam.14829

Bhattacharya, A., Chatterjee, A., Ghosal, S., & Bhattacharya, S. K. (1999). Antioxidant activity of active tannoid principles of *Emblica officinalis* (amla). *Indian Journal of Experimental Biology, 37*(7), 676–680.

Choo, J. H., Rukayadi, Y., & Hwang, J. K. (2006). Inhibition of bacterial quorum sensing by vanilla extract. *Letters in Applied Microbiology, 42*(6), 637–641. https://doi.org/10.1111/j.1472-765X.2006.01928.x

Gopu, V., & Shetty, P. H. (2016). Quercetin-rich onion peel extract with anti-quorum sensing and anti-biofilm activity against *Pseudomonas aeruginosa*. *Journal of Food Science and Technology, 53*(2), 968–974. https://doi.org/10.1007/s13197-015-2059-5

Haussler, S., Becker, T., & Klockgether, J. (2020). Discovery of novel quorum sensing inhibitors targeting the Pqs system in *Pseudomonas* *aeruginosa*. *Frontiers in Microbiology, 11*, 1442. https://doi.org/10.3389/fmicb.2020.01442

Kalia, V. C. (2013). Quorum sensing inhibitors: An overview. *Biotechnology Advances, 31*(2), 224–245. https://doi.org/10.1016/j.biotechadv.2012.10.004

Khan, M. A., Ahmed, R., & Ali, S. (2023). Phytochemicals as quorum sensing inhibitors: A sustainable strategy against multidrug-resistant bacteria. *Microbial Pathogenesis, 178*, 106023. https://doi.org/10.1016/j.micpath.2023.106023

Khan, R., Islam, B., Akram, M., Shakil, S., Ahmad, A., Mehmood, Z., & Khan, A. U. (2009). Antimicrobial activity of five herbal extracts against multi drug resistant (MDR) strains of bacteria and fungus of clinical origin. *Molecules, 14*(2), 586–597. https://doi.org/10.3390/molecules14020586

Krishnaveni, M., & Mirunalini, S. (2010). Therapeutic potential of *Phyllanthus emblica* (amla): The ayurvedic wonder. *Journal of Basic and Clinical Physiology and Pharmacology, 21*(1), 93–105. https://doi.org/10.1515/JBCPP.2010.21.1.93

Lau, G. W., Hassett, D. J., Ran, H., & Kong, F. (2004). The role of pyocyanin in *Pseudomonas aeruginosa* infection. *Trends in Molecular Medicine, 10*(12), 599–606. https://doi.org/10.1016/j.molmed.2004.10.002

Li, Y., Zhou, M., & Wu, J. (2025). Isoliquiritigenin targets multiple quorum sensing systems in *Pseudomonas aeruginosa*. *BMC Microbiology, 25*(1), 112. https://doi.org/10.1186/s12866-025-04298-5

Packiavathy, I. A. S. V., Priya, S., Pandian, S. K., & Ravi, A. V. (2014). Inhibition of biofilm development of uropathogens by curcumin—An anti-quorum sensing agent from turmeric. *Current Microbiology, 68*(1), 7–16. https://doi.org/10.1007/s00284-013-0436-0

Patel, H., Shah, R., & Mehta, P. (2024). Structure-based discovery of PqsD inhibitors as novel quorum sensing modulators. *Medicinal Chemistry Research, 33*(2), 145–157. https://doi.org/10.1007/s00044-024-03267-1

Rasamiravaka, T., Labtani, Q., Duez, P., & El Jaziri, M. (2015). The formation of biofilms by *Pseudomonas aeruginosa*: A review of the natural and synthetic compounds interfering with control mechanisms. *BioMed Research International, 2015*, 1–17. https://doi.org/10.1155/2015/759348

Singh, R., Sharma, D., & Gupta, V. (2021). Plant-derived quorum sensing inhibitors: A new frontier against multidrug-resistant pathogens. *Frontiers in Pharmacology, 12*, 645172. https://doi.org/10.3389/fphar.2021.645172

Singh, R., Shushni, M. A., & Belkheir, A. (2011). Antibacterial and antioxidant activities of *Mentha piperita L.* Arabian Journal of Chemistry, 8*(3), 322–328. https://doi.org/10.1016/j.arabjc.2010.06.019

Singh, S., Singh, S. K., Chowdhury, I., & Singh, R. (2017). Understanding the mechanism of bacterial biofilms resistance to antimicrobial agents. *Open Microbiology Journal, 11*(1), 53–62. https://doi.org/10.2174/1874285801711010053

Vikram, A., Jesudhasan, P. R., Jayaprakasha, G. K., Pillai, S. D., & Patil, B. S. (2010). Citrus limonoids interfere with quorum sensing and biofilm formation in *Vibrio harveyi* and *Escherichia coli* O157:H7. *Food Chemistry, 120*(2), 552–558. https://doi.org/10.1016/j.foodchem.2009.10.052

Zhang, L., Murphy, P. J., Kerr, A., & Tate, M. E. (1993). Agrobacterium conjugation and gene regulation by N-acyl-L-homoserine lactones. *Nature, 362*(6419), 446–448. https://doi.org/10.1038/362446a0

Zhao, J., Shan, T., Mou, Y., & Zhou, L. (2011). Plant-derived natural products for human disease treatment: From bench to clinic. *Phytochemistry Reviews, 10*(2), 197–210. https://doi.org/10.1007/s11101-010-9175-0

Zhou, H., Liu, Y., & Wang, J. (2024). Psoralen as a natural quorum sensing inhibitor targeting *Pseudomonas aeruginosa*. *Applied Microbiology and Biotechnology, 108*(4), 1721–1735. https://doi.org/10.1007/s00253-024-13067-9.

Biochar Addition for Enhanced Biomethane Production from Food Waste: Process Performance and Techno Economic Assessment

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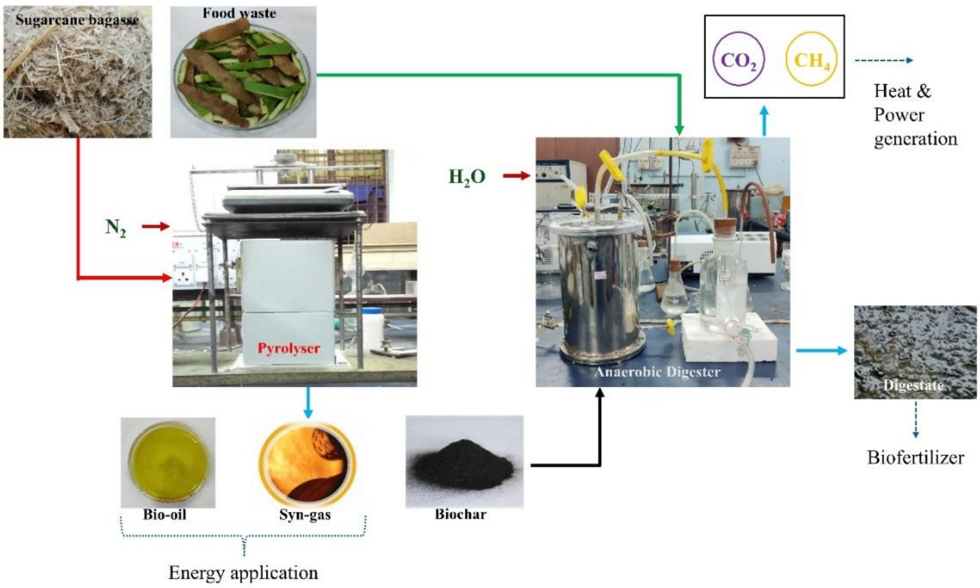
ABSTRACT

Anaerobic digestion (AD) is a sustainable waste-to-energy technology that contributes to the circular bioeconomy and zero-waste goals. However, its efficiency is often constrained by process instabilities such as volatile fatty acid accumulation, ammonia inhibition, and pH fluctuations. Biochar intensifies the biogas production rate and methane content from AD by enhancing buffering capacity, adsorbing inhibitors, promoting biofilm formation, and facilitating direct interspecies electron transfer. Objective of this study is to evaluate the effect of sugarcane bagasse-derived biochar on improving the stability, kinetics, and techno-economics of AD of food waste. In this study, sugarcane bagasse-derived biochar produced through pyrolysis has been applied to the AD of food waste. Based on modified-Gompertz and first-order kinetics determined through lab-scale experimental results, techno-economic analysis has been performed for 10,000 metric tonnes/year. Compared to the control, 29% higher cumulative methane yield of 352 L/kg VS is obtained from biochar-assisted AD. Methane concentration is also improved from 58% to 65%, while the biodegradability index increases to 81.03% against 62.65% for control. Kinetic modelling confirms enhanced process performance with a shorter lag phase and higher hydrolysis rate. Economic analysis indicates that biochar-assisted AD generates higher annual revenue ($184,695 vs. $156,687) compared to the control. Higher investment cost for the digestate storage system is responsible for negative net present values (NPVs) in both scenarios and needs further analysis. The novelty of this work lies in the combined experimental–kinetic–economic assessment of biochar-assisted AD. This study also suggests that utilization of biochar within the AD plant ensures carbon circularity and improves profitability through the production of energy-rich by-products like bio-oil and syngas through digestate-valorization. The outcomes of the research support policies to achieve sustainable deployment in line with the Sustainable Development Goals (SDGs) through the production of valuable additives and by-products from AD waste, i.e., digestate.

Keywords: Anaerobic digestion; Food waste valorization; Biochar; Circular bioeconomy; Techno-economic analysis

AI Disclosure:

GRAPHICAL ABSTRACT



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1. Introduction

The increasing generation of waste, especially in countries like India and the rising global energy demand present major challenges for achieving a sustainable future. Food waste, globally constituting a sizeable portion of total waste, can serve as a valuable resource for renewable energy instead of contributing to greenhouse gas emissions in case of poor management (Lahiri et al., 2023). Harnessing this potential can promote the circular bioeconomy and supports the zero-waste goal by transforming organic residues into useful products rather than disposal. Anaerobic digestion (AD) has emerged as a key technology in this context, providing an environmentally friendly pathway for energy recovery while directly supporting several Sustainable Development Goals (SDGs) set by United Nations, such as affordable and clean energy (SDG 7), responsible consumption and production (SDG 12), and climate action (SDG 13) (Piadeh et al., 2024). Additionally, AD has the advantage of processing the diverse types of bio-waste and needs little energy for setup (Chojnacka & Moustakas, 2024).

In AD, a mixed consortium of bacteria and archaea converts the organic matter into biogas (CH_4 and CO_2) through four sequential steps, i.e., hydrolysis, acidogenesis, acetogenesis and methanogenesis (Zhang et al., 2016). The product biogas can be used in a diverse manner; it can be combusted in a CHP to produce electricity and gas, can be used directly for cooking, or can be upgraded to biomethane to be injected into a CNG grid and used as a vehicle fuel (Paramasivam et al., 2025). Additionally, the by-product of AD, constituted of the undegraded portion of feed biowaste, can serve as a soil amending agent.

Even though AD offers multiple advantages in terms of waste management and bioenergy generation, the process often encounters technical challenges such as long retention period, process instability, and incomplete substrate degradation, fluctuation of pH, accumulation of volatile fatty acids produced during intermediate stages, inhibition due to production of H_2S and NH_3 from S- and N-containing feed materials (Castellano-Hinojosa et al., 2018). These limitations restrict methane yields and reduce the overall efficiency of waste-to-energy conversion. Therefore, improving the stability and methane productivity of AD is crucial in order to enhance its contribution to sustainable waste management and the bio-based economy (Jana et al., 2025).

Traditional techniques for enhancing the performance of the AD process include the use of alkaline additives, such as sodium hydroxide or sodium bicarbonate, to buffer the system, addition of materials like activated carbon as adsorbent, the use of a multi-stage digester to provide ideal conditions for each microbial community, and the use of physical, chemical, and thermal pretreatment techniques to increase the accessibility of difficult-to-digest organic matter to microorganisms (Elsayed et al., 2024). However, all of these approaches need the use of extra chemicals and energy, incurring additional operating expense (OPEX) causing unsustainable situation with respect to environmental protection (Ambaye et al., 2021). In this context, biochar has gained a lot of interest lately as an eco-friendly AD system additive (Chiappero et al., 2022). Biochar is a carbonaceous material produced from biomass through thermochemical processes like pyrolysis, gasification, hydrothermal carbonization, and liquefaction depending upon the intended application (Ghodake et al., 2021). Generation of char can serve as a means of valorizing agricultural wastes, another major waste other than food waste, which is unsuitable for biochemical processes like AD due to high lignin content (S. Li et al., 2019).

Biochar possesses unique physicochemical properties such as high porosity, large surface area, buffering capacity, cation exchange capacity (CEC), electron conductivity, and the presence of useful surface functional groups (S. Li & Skelly, 2023). Pores inside biochar material create favourable conditions for microbial colonization and help ammonia adsorption. Due to the surface functional groups, biochar also helps act as an organic adsorbent via hydrophobic interactions, hydrogen bonding, and van der Waals forces of attraction. These also facilitate direct interspecies electron transfer (DIET) and improve the rate of the process (Cai et al., 2022). Biochar is also reported to have better buffering capacity, thus helping maintain the pH throughout the AD process. As a result, biochar-assisted AD has been reported to improve both methane yield and process robustness. It has also been reported that digestate enriched with biochar exhibits enhanced soil amendment properties (Chiappero et al., 2022).

While addition of biochar to anaerobic digestion is gaining interest, its implementation is still in a nascent stage. Biochar-assisted AD process is not yet widely implemented on a commercial scale. A few pilot and demonstration projects, such as one at a dairy farm in the US, show potential for its adoption (Kumar et al., 2021; Masebinu et al., 2019; Pei et al., 2024). Biochar's commercial implementation in AD systems is still in its emerging phase, with many studies focusing on its effectiveness in improving biogas yield, process stability, and overall efficiency, with potential for broader adoption as challenges related to biochar production costs and long-term performance are addressed. In this regard, a thorough techno-economic analysis (TEA) of the system is required to assess its commercial viability.
Despite the growing recognition of technical advantages of biochar addition in AD, little study has evaluated its effects comprehensively by combining experimental data with kinetic modelling and techno-economic analysis. The added expense of producing biochar also calls into question whether using it in large-scale AD systems is economically feasible. In this study, experiments on the performance of biochar (derived from pyrolysis of sugarcane bagasse) addition to AD of food waste has been conducted, on which kinetic models such as first-order model and Modified Gompertz model has been applied. A complete techno-economic assessment was carried out based on the experimental and kinetic data. In particular, by examining capital expenses (CAPEX), operating expenses (OPEX), and revenue generation, the study evaluates the techno-economic viability of the system and explores the impact of biochar on biomethane production and biodegradability. In addition to advancing our knowledge of how biochar might improve AD, this integrated approach offers important insights into its feasibility within the context of the circular bioeconomy, which helps us reach the SDGs and the global zero-waste objective. The novelty of the study is through its contribution in the elucidation of reaction kinetics and economic aspects of improvement of performance of anaerobic digestion of food waste through biochar addition. One major problem of conducting economic analysis for processes like AD is that there is no thoroughly reviewed standard available for researches to compare their results (e.g. unlike for ethanol production NREL report is often used as standard scenario) (Humbird et al., 2011). Additionally, the repeatability and replicability of the results are also significantly limited by the fact that the majority of research neither disclose the assumptions used to conduct the techno-economic evaluations nor grant access to simulation files (Rajendran & Murthy, 2019). In addition to evaluating the effectiveness and feasibility of adding biochar in anaerobic digestion, this study may assist in the development of a standardized techno-economic assessment (TEA) for AD.

2.0 Materials and Methods

2.1 Materials

Sugarcane bagasse (SB) collected from the local market area was used as the source for biochar production, while food waste (FW) collected from the Jadavpur University canteen, Kolkata, India, was used as the substrate for AD. Food waste consisted of peels and residues of several vegetables such as potato, onion, tomato, gourd, pumpkin, papaya, etc. After collection, both the materials were chopped, sun-dried, and stored at 4°C until utilized for the experiment. The inoculum for Anaerobic digestion was taken from an active anaerobic digester the present group, which was fed on cow dung.

2.2 Methodology

2.2.1 Biochar preparation

Biochar was produced through pyrolysis, conducted in a semi-batch reactor under isothermal conditions at 700°C in an inert atmosphere maintained by a constant flow of nitrogen flow. Beforce fed into the reactor SB dried in a hot air oven (G.B. Enterprises, Kolkata, India) at 105°C for 24 hours. The reactor was equipped with a furnace, a temperature controller (PID controller), and a digital weighing box. The experiment was performed using 15g of biomass (on a dry basis), with a heating rate maintained at 10°C/min. Reactor was connected to a condenser, which temperature was kept at 20°C using cold water circulated from a water bath. After completion of the experiments, the reactor was allowed to cool to room temperature. The solid residue left inside the pyrolysis reactor was collected as the biochar. Biochar was then washed using acetone and water to remove the tar materials before using it to AD.

2.2.2 Anaerobic Digestion

Anaerobic digestion was carried out in semi-batch mode in a 250 conical flask with a 70% working volume. A rubber cork with two apertures on top—one for the gas outflow and another for reactor liquid sampling—was used to seal the flask. Substrate and 10% (V/V) inoculum were added to the reactor, and the total solid (TS) content was adjusted to 6% by combining the proper proportions of FW and water. A magnetic stirrer was used to thoroughly mix the biochar with the food waste slurry. The concentration of the biochar was kept to be 6 g/L. Optimum biochar dosage for biomethane enhancement has been reported to be 5-10 g/L in several studies (Feng et al., 2025; Şenol et al., 2024); dosage higher than 15 g/L can cause inhibition (Asefa et al., 2023). The pH of the system was adjusted to 7.0 by using NaOH as the buffer solution. The reactor was appropriately sealed after filling. To eliminate air from the reactor and establish anerobic condition, nitrogen gas was purged for 5 minutes. The reactor was put in a temperature-controlled environment at 37°C after the air was removed (Scenario S_1 : Biochar-assisted AD).

An identically configured reactor without the addition of biochar served as the control (Scenario S_0 : AD without Biochar).

The internal gas, mostly nitrogen, was released by opening the reactor's gas outlet after a 24-hour period. At this point, the experiment was considered to have begun, and was marked as Day 0 of the study. Biogas was collected on a daily basis through water displacement method up to 30 days. At daily interval, pH of the system was also measured.

2.3 Analytical methods

Proximate analysis of the feedstock was performed using standard ASTM D3172 method to measure the moisture, total solid (TS), volatile solid (VS), fixed carbon (FC) and ash content of the sample (*D05 Committee)*.
A CHNS analyzer (vario MICRO cube elementar, Gurugram, Haryana, India) was used to determine the percentages of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S). The difference was used to calculate the oxygen (O) percentage.

The composition of biogas (CH_4 and CO_2) was examined using gas chromatography (TRACE1110 GC, Thermo Scientific, Waltham, MA, USA) equipped with a TR-FRAME (60 m × 0.25 mm × 0.25 μm) column and a thermal conductivity detector (TCD). The carrier gas, argon, had a flow rate of 10 mL/min. Temperatures for the oven, injection, and detector were set at 40°C, 120°C, and 250°C, respectively.

2.4 Theoretical Calculations

The following stoichiometric formula for AD process was developed by Busswell and Hatfill (Achinas & Euverink, 2016; Murphy & Thanasit Thamsiriroj, 2013) and modified by Boyle (Buswell & Mueller, 1952) based on the assumption that the biodegradable organic matter has been fully digested to methane, carbon dioxide, ammonia, and hydrogen sulfide with no intermidiate product remaining (Eqn. 1). It has also been assumed that the digestion occurred under ideal bacterial conditions at constant temperature with a perfect mixing.

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + dNH_3 + eH_2S \quad (1)$$

Based on the Eqn 1, the theoretical biomethane potential (TBMP) of the material is calculated using Eqn. 2 (Nielfa et al., 2015), taking into account the gases to be ideal gas at NTP:

$$TBMP\ \left(ml\frac{CH_4}{gVS}\right) = \frac{22.4\times\left(\frac{a}{2}+\frac{b}{8}-\frac{c}{4}-\frac{3d}{8}-\frac{e}{4}\right)}{12.017a+1.0079b+15.999c+14.0067d+32.065e} \quad (2)$$

a, b, c, d, and e is determined by dividing the ultimate analysis results of C, H, N, S, and O by their respective molecular weights.

Dividing the experimental biomethane value by the estimated theoretical value yields the biodegradability index (Eqn. 3), which indicates the effectiveness of the AD process to degrade a substrate into biogas *(Nielfa et al., 2015)*.

$$Biodegradability\ index\ (\%) = \frac{Experimental\ biomethane\ potential}{TBMP} \quad (3)$$

To evaluate the performance of the AD process further, the first-order kinetic model (Eqn. 4) and the modified Gompertz model (Eqn. 5) are used to estimate the cumulative biogas production (CBP) and cumulative biomethane production (CMP), respectively [33, 34].

First order kinetic model: $P(t) = P_m \times (1 - exp(-kt))$ (4)

Modified Gompertz model: $B(t) = B_m \times exp\left\{-\exp\left[\frac{r_m \times e}{B_m}(\lambda - t) + 1\right]\right\}$ (5)

P(t) and B(t) represent CBP (L/kg VS) and CMP (L/kg VS) at a digestion time t. P_m and B_m are the simulated maximum CBP and CMP values, respectively, in L/kg VS. r_m (L/kg VS/day) is the simulated maximum daily methane production (DMP). k (days^{-1}) is the rate of hydrolysis, and λ (days) is the lag phase of anaerobic digestion. First-order kinetic model assumes that, the degradration of organic matter by microorganisms is primarily governed by the first-order kinetics of hydrolysis reaction. Whereas, Modified Gompertz Model assumes methanogenic activitiy dominate the biogas production and is the rate limiting step. However, neither of these two models explicitely consider substrate and product inhibition.

2.5 Techno economic assessment

To determine if biochar-assisted AD is more economically viable than a standard AD system, techno economic analyses of S_0 and S_1 are conducted. Along with calculating the payback period (PBP), internal rate of return (IRR), and net present value (NPV), a thorough cash flow analysis is conducted. It has been assumed that the plant will be operational for 20 years, with 8,000 hours of operation per year. Additionally, straight-line depreciation at a 10% interest rate and a 40% tax rate are assumed in the modelling.

The cost of a plant can be categorized in two parts, i.e., CAPEX and OPEX. To estimate the capital cost, the cost of the equipment was determined first.

In the analysis, no additional pyrolysis unit has been considered for the S_1 scenario. Biochar is presumed to have been purchased from the market, which is included in the raw material cost. Hence, the equipment utilized is practically the same in both cases. Mill/shredder was used for feedstock preparation. Then the feedstock was considered to be fed to AD tank for digestion. The biogas produced has been sent to Combined heat and power unit for heat and electricity generation. And the remaining digestate was sent to a storage tank. The equipment used for the investigation is listed in Table 1, along with the base year and references used to determine costs.

Table 1: List of Equipment used

Equipment	Capacity	Cost ($)	Base year	Ref
Mill/shredder	5 MT*/h	41,388.93	2018	(Yang et al., 2018)
AD unit	1500 m^3	1,61,625.00	2015	(Budzianowski & Budzianowska, 2015)
CHP	2 MW	6,03,400.00	2018	(Doddapaneni et al., 2018)
Digestate storage tank	11 MT/d	83,595.68	2018	(Doddapaneni et al., 2018)
*MT → Metric Tons (Tonnes) = 1000 kg				

For estimation of total equipment cost, each reference cost has been multiplied by the capacity correction factor and year correction factor. The capacity correction factor is determined using the following Eqn. 6 (Turton, 2009).

$$\frac{C_a}{C_b} = \left(\frac{A_a}{A_b}\right)^n \qquad (6)$$

where A = equipment cost attribute; C = Purchase cost, n = cost exponent; a and b refer to equipment with required attribute and equipment with base attribute, respectively. As per convention of chemical plants, the cost exponent was assumed to be 0.67. The capacity for plant in the present study was estimated on the basis of experimental results. After the capacity correction, year correction was made by multiplying the ratio of Chemical Engineering Plant Cost Indices (CEPCI) value for 2025 and CEPCI value in the base year, as shown in Eqn. 7 (Turton, 2009).

$$Equipment\ cost_{2025} = \frac{CEPCI_{2025}}{CEPCI_{base\ year}} \times Equipment\ cost_{base\ year} \qquad (7)$$

The Lang factor is then multiplied by the total equipment purchase cost to evaluate the total direct and indirect costs. The total capital expenditure (CAPEX) or capital investment (Turton, 2009) is calculated as the sum of the direct and indirect costs based on previous works (Pati et al., 2023). For the first year, only the cost of the land considered to be the investment. By the second year, 40% of the fixed capital investment had been utilized, and by the third year, rest of the 60% was invested. Straight line depreciation model is used to compute capital investment depreciation over a 15-year period. Over the course of its 20-year working life, the plant runs at 95% capacity in the 16th and 17th years and 90% capacity in the final three.

The sum of the variable and fixed costs of plant operation can be used to estimate operating expenditure (OPEX), also known as the annual operation and maintenance costs. Utilities, labor, raw materials, operating supplies, maintenance and repair, laboratory fees, patents, royalties, and supervision are examples of variable expenses. Conversely, depreciation, financing, municipal taxes, and insurance coverage are examples of fixed costs. Plant overhead costs and other administrative expenses are included in the operation and maintenance charges.

After estimating the capital and operating cost, total annual revenue from the plant was estimated. It has been considered that revenue generation started from 4^{th} year of the operation. Heat and electricity generated from the CHP unit was considered to be the primary source of revenue. In addition, selling the digestate to the farmers and selling renewable energy certificate also assumed to generate revenues.

Cash flow of the plant was evaluated, which represents it represents the net balance of revenues and expenses for each year of operation.

Economic performance of the plant is calculated using the net present value (NPV), internal rate of return (IRR), and payback period (PBP). The NPV, IRR, and PBP have been estimated using the following equations Eqn. 8, Eqn. 9 and Eqn. 10:

$$NPV = -TCI + \sum_{i=1}^{20} \frac{Cash\ flow}{(1+i)^t} \qquad (8)$$

$$\sum_{i=1}^{20} \frac{Cash\ flow}{(1+i)^t} = 0 \qquad (9)$$

$$PBP = \frac{Total\ investment\ cost}{Annual\ income} \qquad (10)$$

NPV represents the difference between present value of cash inflows (revenues) and the present value of cash outflows (capital and operating costs) over the project lifetime. IRR defined as the discount rate at which NPV of a project zero. PBP represents the time required to recover the capital cost, i.e., time taken for the cumulative cash flows to equal the initial investment.

However, in any techno-economic study it must be noted that, costs vary across countries and over time. While it is not mandatory to adopt the same reference framework, a consistent basis is necessary. Accordingly, the calculations in this work are grounded in previously published studies. In this study, costs and prices were considered based on the US market; for other regions, values were converted to USD using the current exchange rate.

A simple flowchart depicting the materials and methods is demonstrated in Fig. 1.

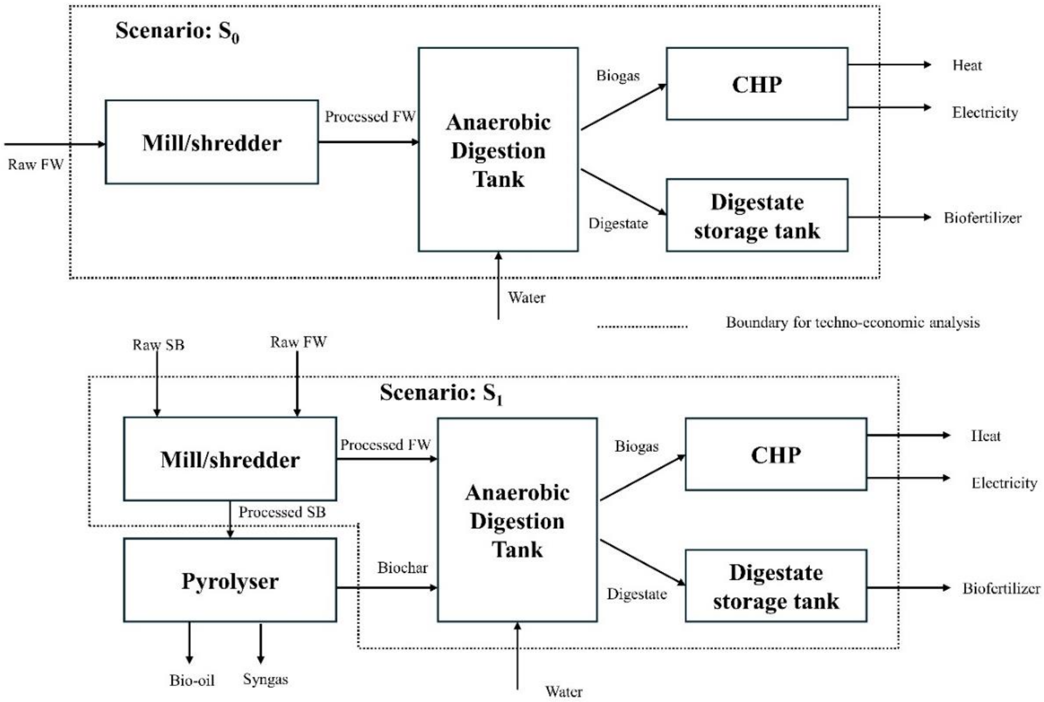

Figure 1: Flowchart for the overall methodology

3.0 Results and discussions

3.1 Performance analysis of anaerobic digestion

Charactarization of the feedstock through proximate and ultimate analysis results is given the Table 2.

Table 2: Proximate and ultimate analysis of food waste

	Proximate Analysis (wt. %)				Ultimate Analysis (wt.%)				
Sample	Moisture	VS	Ash	FC	C	H	N	S	O
Food waste	86.50	81.10	8.81	10.09	49.02	80.43	2.55	0.53	34.47

**VS, Ash, FC and CHNS are calculated in dry basis*

Daily and cumulative biomethane yields are presented in Fig. 2 and Fig. 3, respectively. The results indicate that both the daily production rate and the cumulative yield were enhanced by 29% in the biochar-amended digester (S_1) compared with the control (S_0). Over 30 days of operation, S_1 achieved a cumulative methane production of 352.22 L/kg VS, while the control recorded 272.36 L/kg VS. A shorter lag phase was observed in the biochar-assisted system, with methane generation initiating on day 4, compared to day 6 in the control. Although both systems followed a similar production trend, differences were noted in the timing and magnitude of peak production. The maximum daily methane yield in S_1 was 23.75 L/kg VS on day 15, whereas S_0 reached a peak of 20.42 L/kg VS on day 16. After attaining their respective peaks, methane yields declined progressively and approached stabilization near day 30.

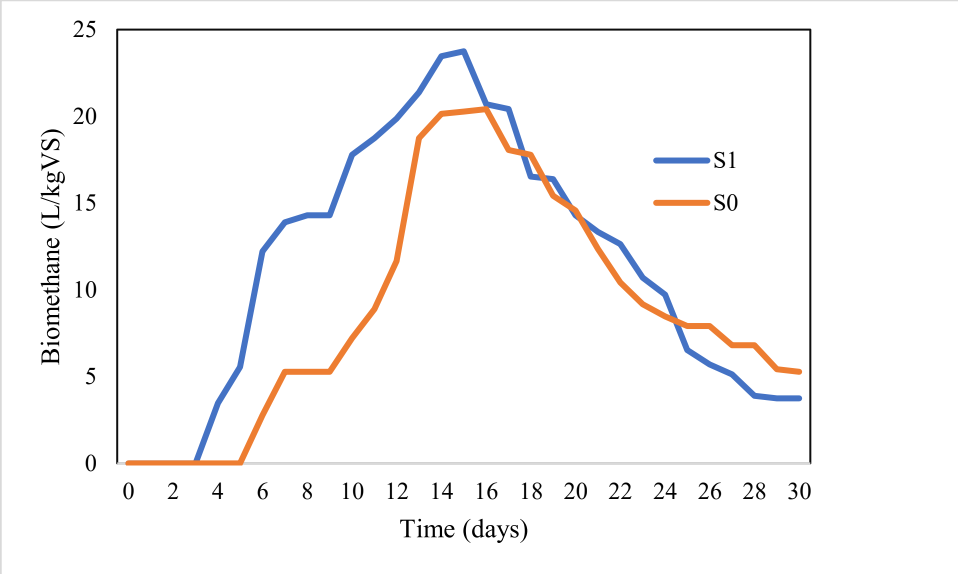

Figure 2: Daily biomethane production

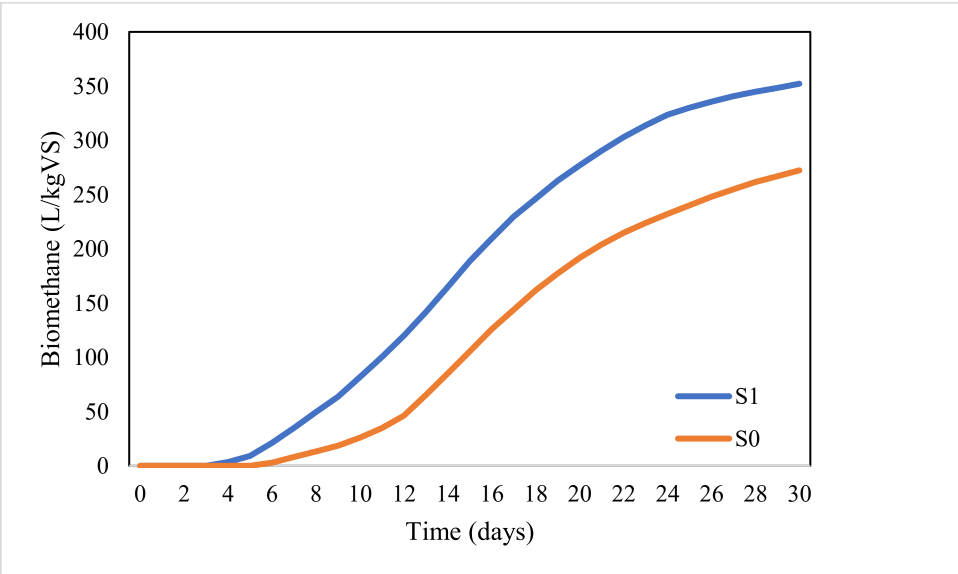

Figure 3: Cumulative biogas production

In addition to higher yields, biochar addition also improved methane quality. The average methane content in biogas from S_1 was 65%, compared to 58% in the control. These findings demonstrate that biochar not only accelerates the onset of biomethane production but also enhances both the rate and methane concentration, contributing to overall process improvement.

The experimental data were fitted using both the modified Gompertz and first-order kinetic models in MATLAB R2023a, and the simulated results were compared with the measured methane production. For S_1, the modified Gompertz model predicted a maximum methane potential (B_m) of 352.22 L/kg VS, a maximum production rate (r_m) of 22.33 L/kg VS·d-1, and a lag phase (λ) of 6.5 days. The model showed strong agreement with the experimental results (R^2 = 0.99, error = %). In contrast, for S_0, the values were lower: B_m=272.36 L/kg VS, r_m=18.79 L/kg VS·d, and λ=9.4 days.

The first-order kinetic model also reflected the positive influence of biochar on hydrolysis. The hydrolysis constant (k) for S_1 was calculated as 5×10^{-4} d^{-1}, compared to 2.9×10^{-4} d^{-1} in the control, consistent with the shorter lag phase observed in S_1. However, the regression coefficients of the first-order model were lower (R^2 = 0.95 for S_1 and 0.88 for S_0) than those obtained from the Gompertz model, indicating a poorer fit. This suggests that simple first-order kinetics may be limited in describing anaerobic digestion performance, particularly in systems influenced by inhibition or enhancement factors.

Biodegradability index, calculated using Equ. 3, further confirmed the positive effect of biochar addition on anaerobic digestion performance. The BI value for S_1 was 81.03%, considerably higher than that of the control (62.65%), indicating improved degradability of food waste with biochar supplementation. A comprehensive comparison of experimental results with simulated parameters from both kinetic models is summarized in Table 3, highlighting the overall enhancement of process performance in the biochar-assisted system. Result of this study agrees well with the data reported by several studies that biochar have the potential of reducing the lag phase by 20–64.4% and increasing biomethane yield upto 90% *(Saif et al., 2022)*. The biochar dosage and pyrolysis temperature applied here fall within the optimum ranges identified in earlier studies. Nonetheless, the influence of these parameters on specific feedstocks and the underlying mechanisms for process enhancement require further investigation. A comparison with earlier research is presented in Table 4, which highlights the improvement in biochar-assisted AD.

Table 3: Performance of anaerobic digestion

Sample	Exp. Methane produced (L/kgVS)	TBMP (L/kgVS)	BI (%)	First order kinetics		Modifed Gompertz			
				k (d^{-1})	R^2	B_m (L/kgVS)	r_m (L/kgVS)	λ (days)	R^2
S_0	272.36	434.70	62.65	0.00029	0.88	288.97	18.79	9.4	0.99
S_1	352.22	434.70	81.03	0.0005	0.95	377.08	22.33	6.5	0.99

Table 4: Comparison of this study with other works

Biochar source	Biochar Production process	Biochar dosage	AD feed material	Findings	References
Rice straw	Pyrolysis 500 ˚C	4 g/L	Sludge	• Lag phase shortened by 28.6% • BC enhanced DIET	(Wang et al., 2018)
Woody biomass	Pyrolysis 400–500 ˚C	12.5 g/L	organic waste from agriculture farm	• Lag phase reduced by 33% • BC proved to have treated ammonia inhibition	(Pant & Rai, 2021)
Cow dung	Pyrolysis 350 ˚C 4 hrs	0.5, 1.0, and 1.5% v/v	Water hyacinth	• Methane content improved by 9.33 – 19.8% • The highest methane yield and VS removal (77.4%) were observed for 1% biochar dose.	(Suthar et al., 2022)
Corn straw	Pyrolysis 300, 600, 900 ˚C 1h	10 g/L	Food waste	• BC prepared at 900 ˚C had the best effect • Maximum methane production rate increased by 17.80%.	(Sun et al., 2022)
Food waste digestate	Pyrolysis 500, 550, and 600 ◦C	10, 20, and 30 g/L	Food waste	• The optimal pyrolysis temperature, particle size, and dosage of • BC were found to be 565 ◦C, 0–0.30 mm, and 15.52 g/L, respectively. • Reduced ammonia toxicity	(Peng et al., 2023)

Biochar source	Biochar Production process	Biochar dosage	AD feed material	Findings	References
Sugarcane bagasse	Pyrolysis 500 °C 1 h	6 g/L	Food waste	• Lag phase shortened by 31 % • Maximum methane production rate increased by 29%. • Methane content increased by 16%	This study

3.2 Techno economic analysis

3.2.1 Cost estimation

The AD plant was designed to have a process capacity of treating 10,000 MT of slurry per year. A 1200 m^3 AD tank is needed to process the volume of slurry each year, according to estimates based on data from the literature (Budzianowski & Budzianowska, 2015; Doddapaneni et al., 2018; Y. Li et al., 2018; Rajendran & Murthy, 2019). The mill/shredder capacity is estimated to be 0.56 MT/y based on the calculation for the amount of feedstock needed to make this amount of slurry (Budzianowski & Budzianowska, 2015; Yang et al., 2018). Based on the experimental biomethane potential value calculated from lab-scale studies and scaled to the scale of 10,000 MT/y, the plant is expected to generate 1,69,067 and 1,30,733 m^3 of biogas yearly with and without biochar, respectively. It is assumed that the installed CHP unit has a 40% electricity conversion efficiency and a 45% heat conversion efficiency. The plant is expected to generate 676.27 MWh of electricity and 760.80 MWh of heat when operated with biochar, and 522.93 MWh of electricity and 588.30 MWh of heat when operated without biochar, according to calculations that take into account the heating value of methane to be 10 kWh/m^3. For this operation, a 50-kW power CHP is sufficient (Budzianowski & Budzianowska, 2015; Doddapaneni et al., 2018). For S_1 and S_0, the amounts of digestate generated have been calculated to be 9821 and 9852 MT/year, respectively. It implies that a digestate storage tank needs to have a capacity of 26.90 MT/d (Budzianowski & Budzianowska, 2015; Doddapaneni et al., 2018).

Inserting the values of estimated capacities into Eqn. 6 and Eqn. 7, the purchased cost of individual equipment is determined (base costs at specific capacities in the reference year were taken from the literature and given in Table 1). CEPCI values for the selected base years were taken from the updated monthly data published in *Chemical Engineering* magazine ("The Chemical Engineering Plant Cost Index ®," 2014), which is based on the information of U.S. Department of Labor's Bureau of Labor Statistics (Databases, Tables & Calculators by Subject, n.d.). The Total Equipment Purchase Cost (TEPC) was calculated to be $437,557. The estimated equipment costs are summarized in Table 5 and the percentage distribution of the individual units in TEPC is illustrated in Fig. 4.

Table 5: Estimation of total equipment purchases cost (TEPC)

Unit	Capacity	Cost ($)
Mill/Shredder	0.56 MT/h	12,612.82
AD Tank	1200 m^3	1,58,819.10
CHP	50 kW	68,022.85
Digestate storage tank	26.90 MT/d	2,00,102.90
TEPC		4,39,557.70

Among the major cost contributors, the digestate storage unit accounted for the largest share (46%), followed by the anaerobic digester (36%). Preprocessing and CHP units combined contributed less than 20%, with preprocessing unit (mill/shredder) being the smallest contributor (only 3% of TEPC). This trend highlights the capital-intensive nature of digestate management due to large effluent volumes and the need for adequate storage infrastructure prior to utilization or disposal. Reducing digestate volume by feeding feedstocks with less moisture content and valorizing digestate into further value-added fuels or other products could enhance the profitability of the system substantially. However, this area is this less emphasized in an AD plant and need further research.

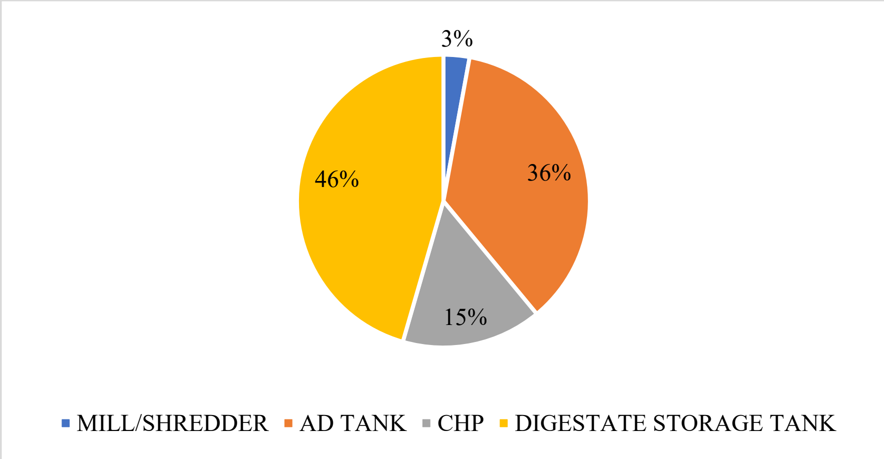

Figure 4: Percentage share of cost of different units in Total Equipment Cost

Using the equipment cost as the basis, the Total Capital Investment (TCI) was estimated to be \$1,758,793.53. Considering installation, instrumentation, piping, electrical systems, civil works, and auxiliary requirements, the total direct cost (TDC) was calculated as \$1.09 million. Adding indirect expenses such as engineering, construction, legal, and contractor's fees led to a total indirect cost (TIC) of \$0.39 million. TCI also comprised contingency, working capital and land acquisition costs (Pati et al., 2023). A detailed breakdown of these cost components is presented in Table 6.

Table 6: Estimation of total capital investment [Units of Costs in USD]

TEPC		4,39,557.72
Equipment installation	39% of TEPC	
Instrumentation and control	26% of TEPC	
Piping	31% of TEPC	
Electrical systems	10% of TEPC	
Buildings	29% of TEPC	
Yard improvement	12% of TEPC	
TDC		10,85,707.58
Engineering and supervision	32% of TEPC	
Construction expenses	34% of TEPC	
Legal expenses	4 % of TEPC	
Contractors fee	19% of TEPC	
TIC		3,91,206.37
Contingency	0.02×(TDC+TIC)	29,538.28
Working capital	0.15×(TDC + TIC+ Contingency)	2,25,967.83
Land	0.06×TEPC	26,373.46
TCI		**17,58,793.53**

**All the units of the costs are in USD*

Overall, the TCI distribution indicates that while equipment forms the backbone of investment, substantial contributions also come from installation, engineering, and financial provisions, reflecting the multi-dimensional cost nature of AD projects.

Although the capital expenditure was comparable for both scenarios, operating costs varied due to differences in raw material expenses. For S_0, materials cost included only cost of food waste, whereas for S_1, the cost of biochar is added to that of food waste, resulting in higher material costs. In the U.S. market, municipal solid waste (MSW) is valued at \$56.8 per dry ton, while the global average price of biochar is considered \$862 per ton (Garcia et al., 2022). Material cost was calculated based on that. Labor costs were estimated following the methodology of Schwartz et al. (2013), whereas only water required to make up the slurry is considered as utilities. Electricity required to maintain the AD tank temperature in the mesophilic range has been excluded from the utility calculations. Tap water is used, and the price of tap water is taken to be 0.03 USD/kg (Schwartz et al., 2025).

The annual operating cost was estimated to be $965,899 for S_1, and $912,566 for S_0. A detailed breakdown of operating costs is presented in Table 7. The higher cost in S_1 was primarily due to biochar procurement costs, which increased the material cost from $30,000 to $78,000 in S_1. Sourcing low-cost biochar or utilizing digestate-derived biochar could reduce the operational expenses and improve the overall profitability.

Table 7: Estimation of operating cost

Item	S_0		S_1	
	Costs (USD)	Percentage (%)	Costs (USD)	Percentage (%)
Materials	30,000.00	3.29	78,000.00	8.08
Utilities	16,666.67	1.83	16,666.67	1.73
Labor	2,54,290.00	27.87	2,54,290.00	26.33
Operating supervision	38,143.50	4.18	38,143.50	3.95
Maintenance and repairs	48,351.35	5.3	48,351.35	5.01
Operating supplies	7,252.70	0.79	7,252.70	0.75
Laboratory charges	38,143.50	4.18	38,143.50	3.95
Property tax	30,129.04	3.3	30,129.04	3.12
Financing (interest)	87,939.68	9.64	87,939.68	9.1
Insurance	15,064.52	1.65	15,064.52	1.56
Overhead	2,04,470.90	22.41	2,04,470.90	21.17
Administration	50,858.00	5.57	50,858.00	5.27
Royalties	8,940.48	1	9,473.81	1
Distribution and sales	44,702.40	5	47,369.07	5
Research and development	35,761.92	4	37,895.25	4
Total operating cost	9,12,566.50		9,65,899.90	

Fig. 5 presents the percentage distribution of different factors in OPEX.

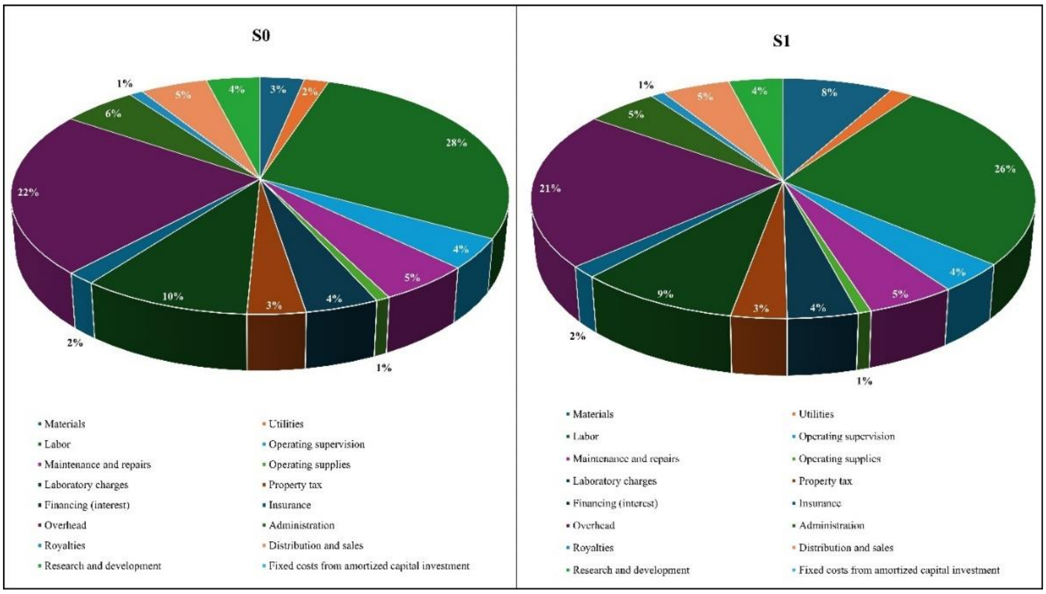

Figure 5: Percentage distribution of factors affecting total operating cost

The largest operating expenses were attributed to labour charge (28%), followed by overhead (22%) and financing charges (9–10%). Other fixed contributions, such as property tax, insurance, and maintenance/repairs, represented smaller but consistent shares of the total. It is evident that the higher proportion of material cost in S_1 (8% compared to that of 3% in S_0) reflected the earlier claim. This highlights the sensitivity of annual OPEX to feedstock procurement and handling. Interestingly, research and development, royalties, and distribution showed minor increases in S_1, suggesting higher throughput leads to proportionate cost escalation in support services.

3.2.2 Revenues

The AD system generates both thermal and electrical energy through combined heat and power conversion. For this study, CHP efficiencies were assumed to be 40% for thermal energy and 45% for electricity generation (Aravani & Papadakis, 2024). Overall, based on the experimental biomethane yields of 322.22 L/kg VS for S_1 and 272.36 L/kg VS for S_0, the projected annual biomethane production in a scaled-up plant treating 10,000 kg was determined to be 169,067 m³ and 130,733 m³ for S_1 and S_0, respectively. Considering the heating value of methane as 10 MWh/m³, the corresponding energy potential was estimated. The minimum selling prices (MSP) were considered as $75.43/MW for thermal energy and $96.54/MW for electrical energy. Digestate produced from this plant was calculated to be 9821 t/y and 9852 t/y for S_1 and S_0, respectively, and was assumed to be marketed to farmers at a rate of $4.31/ton (Budzianowski & Budzianowska, 2015). Additional revenue was incorporated from renewable energy certificates (REC), valued at $2.5/MW of renewable energy in the U.S. market (Rajendran & Murthy, 2019).

Based on these assumptions, the total annual revenue was estimated at $184,695 for S_1 and $156,687 for the control (S_0). A summary of these revenue streams is provided in Table 8.

Table 8: Estimation of total annual revenue

	S_0	S_1
Electricity produced (MWh/y)	522.93	676.27
MSP ($/MWh)	96.54	96.54
Revenue from electricity ($/y)	50,486.08	65,289.49
Heat produced (MWh/y)	588.30	760.80
MSP ($/MWh)	75.43	75.43
Revenue from heat($/y)	44,372.53	57,383.34
Digestate produced (t/y)	9851.80	9821.00
MSP ($/t)	4.31	4.31
Revenue from digestate ($/y)	60,520.68	60,331.47
Revenue from REC ($/y)	1,307.33	1,690.67
Total Revenue ($/y)	**1,56,686.60**	**1,84,695.00**

Electricity sales contributed for the highest share of revenue, which was about 27-35% of the total annual revenue. Heat utilization also accounted for fairly high share, about 31-33% of the total revenue. Digestate utilization was consistent for both the cases, generating around $60,000/year, accounting for 32-38% share. RECs contributed the least, <1%.

The higher revenue in S_1 resulted from its increased methane production, which translates into greater energy recovery potential. Importantly, revenues from digestate utilization and RECs, though smaller in proportion, contributed additional value streams, highlighting the multifaceted economic benefits of AD beyond biomethane generation. This underlines that biochar-assisted AD not only improves process efficiency but also enhances the revenue potential of the system.

Fig. 6 displays the overall comparison between the CAPEX, OPEX, and revenues of the AD system with and without biochar.

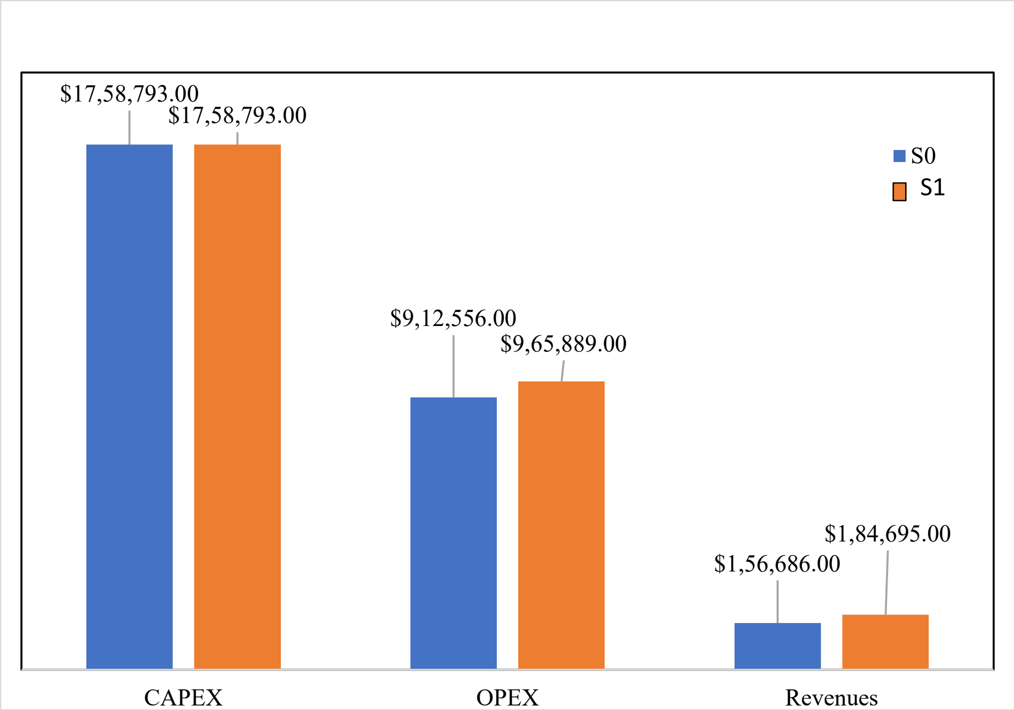

Figure 6: Comparison of CAPEX, OPEX and Revenues

3.2.3 Economic performance

The economic performance of the AD systems was evaluated using standard financial indicators, including net present value (NPV), internal rate of return (IRR), and payback period. In both scenarios, the NPV was found to be negative, with values of –\$3.98 million for S_1 and –\$3.89 million for S_0. Eventually, determination of IRR and PBP was not possible, as their calculation requires a positive NPV.
While a negative NPV does not necessarily indicate a negative ROI (Return on investment), when the project results in an actual financial loss (i.e., when undiscounted inflows are lower than outflows), the ROI also becomes negative, as observed in this case. Thus, the project leads to a net monetary loss in the absence of additional incentives or supportive policies.

These results indicate that, under the current assumptions and market conditions, stand-alone AD is not economically profitable. Outcome of this study resembles with previous studies, which reported that low biogas production coupled with high liquid digestate generation limits the economic viability of AD (Y. Li et al., 2020; Shinde et al., 2025). Although the addition of biochar improved methane yield and generated additional revenues, the benefit was insufficient to overcome high CAPEX and OPEX burden, resulting in no substantial improvement in project profitability.

This outcome emphasizes that the economic feasibility of AD systems is highly sensitive to feedstock cost, biochar pricing, and revenue streams from byproducts. Integrating the biochar production system within the AD plant can reduce biochar production cost while also offering the possibility of value addition to digestate through pyrolysis. Besides producing biochar, pyrolysis also produces valuable products like bio-oil and syngas, opening the possibility of further revenue generation. Installation of an efficient digestate separation system and bio-oil upgrading technologies needs to be considered in that case. Without cost reduction for biochar production, advancement of digestate storage technology and by-product valorization, strategic interventions in policy support, additional tariffs for renewable energy, carbon credit mechanism, such projects may struggle to achieve commercial adoption (Rajendran & Murthy, 2019).

4.0 Conclusion

This study demonstrated that the addition of biochar significantly boosted the anaerobic digestion performance of food waste, reflected by improved biodegradability, reduced lag phase, and a substantial increase in methane production. In addition to improve process efficiency, biochar production from agricultural residues such as sugarcane bagasse further supports resource valorization within a circular bioeconomy framework. The biochar-assisted system produced 352.22 L/kg VS of biomethane over time, a

29% increase than the control. In Kinetic analysis, the first-order kinetic model showed lower accuracy, while the modified Gompertz model exhibited a strong fit to the experimental data, demonstrating its applicability for predicting methane production dynamics. The biodegradability index, which showed a value of 81.03% for the biochar-assisted AD and 62.65% for the control, further validated its superior performance. While this study is consistent with previous reports highlighting improvements in AD stability, process kinetics, and methane yield with biochar addition, precise microbial and physicochemical interactions driving these improvements remain poorly understood. A continued and detailed investigation into the underlying mechanisms is therefore necessary before drawing any deterministic conclusions.

According to the economic analysis, digestate storage unit and the digester tank were the major contributors to capital costs, while biochar procurement increased the operating expenditure of S_1 relative to the control. Although higher methane yields and additional revenue streams from energy sales, digestate, and RECs were achieved in S_1, the overall financial indicators, specifically the negative NPV value, suggested that stand-alone AD under current assumptions remains non-profitable, as showed in several studies. Future profitability will depend on optimisation of digestate valorisation pathways, the reduction of biochar costs, and investigation of strategies like production of biochar directly from AD effluent, i.e., digestate. This integrated approach of combining AD and biochar producing technology of Pyrolysis within a same plant, could address high biochar procurement expenses and digestate management simultaneously. However, the additional cost and energy for setting up the pyrolysis unit and installation of an effective drying unit needed to be considered for such a system. Advancement of technologies for biooil upgradation also required for pyrolysis unit to ensure economic returns.

Nevertheless, technological improvements itself may not guarantee financial profitability. Supportive policy frameworks, government incentives, favourable carbon credit schemes, and increased social acceptance – all are necessary for the successful implementation of biochar-assisted AD and integrated biorefinery systems. All things considered, scaling up these kinds of systems, advancing the circular bioeconomy, and achieving global sustainability and climate goals will depend largely on the alignment of technological, economic, and policy measures.

References

Achinas, S., & Euverink, G. J. W. (2016). Theoretical analysis of biogas potential prediction from agricultural waste. Resource-Efficient Technologies, 2(3), 143–147. https://doi.org/10.1016/j.reffit.2016.08.001

Ambaye, T. G., Rene, E. R., Nizami, A.-S., Dupont, C., Vaccari, M., & Van Hullebusch, E. D. (2021). Beneficial role of biochar addition on the anaerobic digestion of food waste: A systematic and critical review of the operational parameters and mechanisms. Journal of Environmental Management, 290, 112537. https://doi.org/10.1016/j.jenvman.2021.112537

Aravani, V. P., & Papadakis, V. G. (2024). Technoeconomic assessment for the viable exploitation of biomass residues by an innovative pyrolysis-anaerobic digestion processing plant. Environmental Research, 243, 117835. https://doi.org/10.1016/j.envres.2023.117835

Asefa, S. K., Ancha, V. R., Habtu, N. G., & Sundar, L. S. (2023). Experimental evaluation on the effect of biochar addition with anaerobic digestion of the tannery wastewater to improve biogas production. Water Reuse, 13(3), 459–474. https://doi.org/10.2166/wrd.2023.061

Budzianowski, W. M., & Budzianowska, D. A. (2015). Economic analysis of biomethane and bioelectricity generation from biogas using different support schemes and plant configurations. Energy, 88, 658–666. https://doi.org/10.1016/j.energy.2015.05.104

Buswell, A. M., & Mueller, H. F. (1952). Mechanism of Methane Fermentation. Industrial & Engineering Chemistry, 44(3), 550–552. https://doi.org/10.1021/ie50507a033

Cai, Y., Zhu, M., Meng, X., Zhou, J. L., Zhang, H., & Shen, X. (2022). The role of biochar on alleviating ammonia toxicity in anaerobic digestion of nitrogen-rich wastes: A review. Bioresource Technology, 351, 126924. https://doi.org/10.1016/j.biortech.2022.126924

Castellano-Hinojosa, A., Armato, C., Pozo, C., González-Martínez, A., & González-López, J. (2018). New concepts in anaerobic digestion processes: Recent advances and biological aspects. Applied Microbiology and Biotechnology, 102(12), 5065–5076. https://doi.org/10.1007/s00253-018-9039-9

Chiappero, M., Fiore, S., & Berruti, F. (2022). Impact of biochar on anaerobic digestion: Meta-analysis and economic evaluation. Journal of Environmental Chemical Engineering, 10(6), 108870. https://doi.org/10.1016/j.jece.2022.108870

Chojnacka, K., & Moustakas, K. (2024). Anaerobic digestate management for carbon neutrality and fertilizer use: A review of current practices and future opportunities. Biomass and Bioenergy, 180, 106991. https://doi.org/10.1016/j.biombioe.2023.106991

D05 Committee. (n.d.). Practice for Proximate Analysis of Coal and Coke. ASTM International. https://doi.org/10.1520/D3172-13R21E01
Databases, Tables & Calculators by Subject. (n.d.). Bureau of Labor Statistics. Retrieved September 5, 2025, from https://www.bls.gov/data/
Doddapaneni, T. R. K. C., Praveenkumar, R., Tolvanen, H., Rintala, J., & Konttinen, J. (2018). Techno-economic evaluation of integrating torrefaction with anaerobic digestion. Applied Energy, 213, 272–284. https://doi.org/10.1016/j.apenergy.2018.01.045
Elsayed, A., Laqa Kakar, F., Mustafa Abdelrahman, A., Ahmed, N., AlSayed, A., Sherif Zagloul, M., Muller, C., Bell, K. Y., Santoro, D., Norton, J., Marcus, A., & Elbeshbishy, E. (2024). Enhancing anaerobic digestion Efficiency: A comprehensive review on innovative intensification technologies. Energy Conversion and Management, 320, 118979. https://doi.org/10.1016/j.enconman.2024.118979
Feng, K., Ansari, A. J., Zhang, N., Peng, Y., & Song, X. (2025). Biochar addition to mitigate oil inhibition in anaerobic digestion of food wastewater: Microbial insights from biochemical methane potential tests. Environmental Technology & Innovation, 37, 104000. https://doi.org/10.1016/j.eti.2024.104000
Garcia, B., Alves, O., Rijo, B., Lourinho, G., & Nobre, C. (2022). Biochar: Production, Applications, and Market Prospects in Portugal. Environments, 9(8), 95. https://doi.org/10.3390/environments9080095
Ghodake, G. S., Shinde, S. K., Kadam, A. A., Saratale, R. G., Saratale, G. D., Kumar, M., Palem, R. R., AL-Shwaiman, H. A., Elgorban, A. M., Syed, A., & Kim, D.-Y. (2021). Review on biomass feedstocks, pyrolysis mechanism and physicochemical properties of biochar: State-of-the-art framework to speed up vision of circular bioeconomy. Journal of Cleaner Production, 297, 126645. https://doi.org/10.1016/j.jclepro.2021.126645
Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D., & Dudgeon, D. (2011). Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover (No. NREL/TP-5100-47764, 1013269; p. NREL/TP-5100-47764, 1013269). https://doi.org/10.2172/1013269
Jana, R., Ikbal, S., & Chowdhury, R. (2025). Boosting of energy efficiency and by-product quality of anaerobic digestion of Kitchen Waste: Hybridization with pyrolysis using Zero-Waste strategy. Energy Conversion and Management, 324, 119290. https://doi.org/10.1016/j.enconman.2024.119290
Kumar, M., Dutta, S., You, S., Luo, G., Zhang, S., Show, P. L., Sawarkar, A. D., Singh, L., & Tsang, D. C. W. (2021). A critical review on biochar for enhancing biogas production from anaerobic digestion of food waste and sludge. Journal of Cleaner Production, 305, 127143. https://doi.org/10.1016/j.jclepro.2021.127143
Lahiri, A., Daniel, S., Kanthapazham, R., Vanaraj, R., Thambidurai, A., & Peter, L. S. (2023). A critical review on food waste management for the production of materials and biofuel. Journal of Hazardous Materials Advances, 10, 100266. https://doi.org/10.1016/j.hazadv.2023.100266
Li, S., Harris, S., Anandhi, A., & Chen, G. (2019). Predicting biochar properties and functions based on feedstock and pyrolysis temperature: A review and data syntheses. Journal of Cleaner Production, 215, 890–902. https://doi.org/10.1016/j.jclepro.2019.01.106
Li, S., & Skelly, S. (2023). Physicochemical properties and applications of biochars derived from municipal solid waste: A review. Environmental Advances, 13, 100395. https://doi.org/10.1016/j.envadv.2023.100395
Li, Y., Han, Y., Zhang, Y., Luo, W., & Li, G. (2020). Anaerobic digestion of different agricultural wastes: A techno-economic assessment. Bioresource Technology, 315, 123836. https://doi.org/10.1016/j.biortech.2020.123836
Li, Y., Xu, F., Li, Y., Lu, J., Li, S., Shah, A., Zhang, X., Zhang, H., Gong, X., & Li, G. (2018). Reactor performance and energy analysis of solid state anaerobic co-digestion of dairy manure with corn stover and tomato residues. Waste Management, 73, 130–139. https://doi.org/10.1016/j.wasman.2017.11.041
Masebinu, S. O., Akinlabi, E. T., Muzenda, E., & Aboyade, A. O. (2019). A review of biochar properties and their roles in mitigating challenges with anaerobic digestion. Renewable and Sustainable Energy Reviews, 103, 291–307. https://doi.org/10.1016/j.rser.2018.12.048
Murphy, J. D. & Thanasit Thamsiriroj. (2013). Fundamental science and engineering of the anaerobic digestion process for biogas production. In The Biogas Handbook (pp. 104–130). Elsevier. https://doi.org/10.1533/9780857097415.1.104
Nielfa, A., Cano, R., & Fdz-Polanco, M. (2015). Theoretical methane production generated by the co-digestion of organic fraction municipal solid waste and biological sludge. Biotechnology Reports, 5, 14–21. https://doi.org/10.1016/j.btre.2014.10.005
Pant, A., & Rai, J. P. N. (2021). Application of Biochar on methane production through organic solid waste and ammonia inhibition. Environmental Challenges, 5, 100262. https://doi.org/10.1016/j.envc.2021.100262
Paramasivam, P., Alruqi, M., & Ağbulut, Ü. (2025). Waste to energy: Enhancing biogas utilization in dual-fuel engines using machine learning based prognostic analysis. Fuel, 381, 133093. https://doi.org/10.1016/j.fuel.2024.133093
Pati, S., De, S., & Chowdhury, R. (2023). Integrated techno-economic, investment risk and life cycle

analysis of Indian lignocellulosic biomass valorisation via co-gasification and syngas fermentation. Journal of Cleaner Production, 423, 138744. https://doi.org/10.1016/j.jclepro.2023.138744

Pei, S., Fan, X., Qiu, C., Liu, N., Li, F., Li, J., Qi, L., & Wang, S. (2024). Effect of biochar addition on the anaerobic digestion of food waste: Microbial community structure and methanogenic pathways. Water Science & Technology, 90(3), 894–907. https://doi.org/10.2166/wst.2024.199

Peng, Y., Li, L., Dong, Q., Yang, P., Liu, H., Ye, W., Wu, D., & Peng, X. (2023). Evaluation of digestate-derived biochar to alleviate ammonia inhibition during long-term anaerobic digestion of food waste. Chemosphere, 311, 137150. https://doi.org/10.1016/j.chemosphere.2022.137150

Piadeh, F., Offie, I., Behzadian, K., Rizzuto, J. P., Bywater, A., Córdoba-Pachón, J.-R., & Walker, M. (2024). A critical review for the impact of anaerobic digestion on the sustainable development goals. Journal of Environmental Management, 349, 119458. https://doi.org/10.1016/j.jenvman.2023.119458

Rajendran, K., & Murthy, G. S. (2019). Techno-economic and life cycle assessments of anaerobic digestion – A review. Biocatalysis and Agricultural Biotechnology, 20, 101207. https://doi.org/10.1016/j.bcab.2019.101207

Saif, I., Thakur, N., Zhang, P., Zhang, L., Xing, X., Yue, J., Song, Z., Nan, L., Yujun, S., Usman, M., Salama, E.-S., & Li, X. (2022). Biochar assisted anaerobic digestion for biomethane production: Microbial symbiosis and electron transfer. Journal of Environmental Chemical Engineering, 10(3), 107960. https://doi.org/10.1016/j.jece.2022.107960

Schwartz, E., He, H., Ogunseitan, O. A., & Schoenung, J. M. (2025). Phenol production from pyrolysis of waste printed circuit boards: Life cycle and techno-economic assessment. Resources, Conservation and Recycling, 215, 108019. https://doi.org/10.1016/j.resconrec.2024.108019

Şenol, H., Çolak, E., Elibol, E. A., Hassaan, M. A., & El Nemr, A. (2024). Optimisation of biochar dose in anaerobic co-digestion of green algae and cattle manure using artificial neural networks and response surface methodology. Chemical Engineering Journal, 493, 152750. https://doi.org/10.1016/j.cej.2024.152750

Shinde, R., Hackula, A., Marycz, M., Bose, A., O'Shea, R., Barth, S., Murphy, J. D., & Wall, D. M. (2025). Dynamic anaerobic digestion-based biorefineries for on-demand renewable energy and bioproducts in a circular bioeconomy. Trends in Biotechnology, 43(5), 1140–1165. https://doi.org/10.1016/j.tibtech.2025.01.005

Sun, Z., Feng, L., Li, Y., Han, Y., Zhou, H., & Pan, J. (2022). The role of electrochemical properties of biochar to promote methane production in anaerobic digestion. Journal of Cleaner Production, 362, 132296. https://doi.org/10.1016/j.jclepro.2022.132296

Suthar, S., Sharma, B., Kumar, K., Rajesh Banu, J., & Tyagi, V. K. (2022). Enhanced biogas production in dilute acid-thermal pretreatment and cattle dung biochar mediated biomethanation of water hyacinth. Fuel, 307, 121897. https://doi.org/10.1016/j.fuel.2021.121897

The Chemical Engineering Plant Cost Index ®. (2014, November 21). Chemical Engineering. https://www.chemengonline.com/pci-home/

Turton, R. (Ed.). (2009). Analysis, synthesis, and design of chemical processes (3rd ed). Prentice Hall.

Wang, C., Liu, Y., Gao, X., Chen, H., Xu, X., & Zhu, L. (2018). Role of biochar in the granulation of anaerobic sludge and improvement of electron transfer characteristics. Bioresource Technology, 268, 28–35. https://doi.org/10.1016/j.biortech.2018.07.116

Yang, Y., Wang, J., Chong, K., & Bridgwater, A. V. (2018). A techno-economic analysis of energy recovery from organic fraction of municipal solid waste (MSW) by an integrated intermediate pyrolysis and combined heat and power (CHP) plant. Energy Conversion and Management, 174, 406–416. https://doi.org/10.1016/j.enconman.2018.08.033

Zhang, Q., Hu, J., & Lee, D.-J. (2016). Biogas from anaerobic digestion processes: Research updates. Renewable En*ergy*, *98*, 108–119. https://doi.org/10.1016/j.renene.2016.02.029.

Assessing circular economy through sustainable solid waste management: Case of Tier-II Indian City - Cuttack

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ABSTRACT

As the cities grows, the challenges to settle proper infrastructure in Tier-II cities in India also grows as most demand and focus lie on Tier-I cities. Solid waste management (SWM) services, being one of the major infrastructural concerns is mostly overlooked in many Tier-II cities in India. Though municipalities have addressed many challenges in SWM services, yet it continues to face issues related to collection, treatment and management. Financial support for SWM services is an important question that needs to be addressed in academic research. This research aims to develop effective circular economy and sustainable solid waste management strategy for Cuttack City, a Tier-II city in India. This study focuses on estimating municipal solid waste (MSW) generation, evaluating existing management systems, identifying opportunities for improvement and formulating a financial model. Primary data was gathered through household surveys to understand waste generation behaviours, segregation practices, and willingness to pay (WTP) for enhanced waste management services. Secondary data, sourced from governmental reports and prior studies, was analysed to estimate waste generation, evaluate current solid waste management practices, and propose improvements. Analysis revealed that 70% of households in Cuttack City are willing to segregate and recycle waste, and an average of 80% of household are willing to pay for daily collection, Odor free services and street cleaning. The revenue generated out of WTP can be further used for investing on transportation of waste, labour wages, composting and recycling, which in turn returns the after-sale value in marketing.

Keywords: Waste Segregation, Landfilling, Recycling, Circular economy, Willingness to pay.

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1. Introduction and conceptual background

Solid waste management (SWM) in developing countries faces significant challenges, including low collection rates, inadequate infrastructure, reliance on informal waste sectors, financial constraints, and limited public awareness (Paes, 2021). Many cities, such as Dhaka, Bangladesh, dispose of over 60% of their waste in open dumps, leading to severe environmental and health issues (Guerrero, Maas, & Hogland, 2013). Similarly, in India, the increasing economic prosperity and urbanization have led to a significant rise in waste generation, posing a pressing environmental challenge. According to Inductus GCC, India is witnessing a huge shift of urban population from Tier-I cities to Tier-II cities, due to escalating cost, talent competitions in Tier-I cities and fast development of infrastructure, coming of industries and employment opportunities in Tier-II cities (CBRE, 2022) (Singh, 2024). Such growth of urbanisation in Tier-II cities, poses a great challenge on SWM issues (CPCB, 2022) that is prevailing these days. While proper waste management is crucial for mitigating public health risks and environmental degradation, this article also presents opportunities for resource recovery, return of investments through various SWM services and disposals.

1.1 Tier-II cities and its challenges

Most tier-II cities in India, struggle with inefficient solid waste management (SWM) practices, leading to a range of negative consequences (Mondal & Mandal, 2024). Such scenario is still prevalent mostly in developing countries (Dipeolu, Akpa, & Fadamiro, 2020). Tier-II cities like Gwalior (Madhya Pradesh), Moradabad (Uttar Pradesh), Bhubaneswar (Odisha) are some of the tier-II cities that are facing challenges in SWM services despite being smart proposals, while few cities like Indore (Madhya Pradesh), Mysore (Karnataka), Navi Mumbai, Ambikapur (Chhattisgarh) have proven best practices in SWM services (Sharholy et al., 2008; Central Pollution Control Board, 2016). Financial limitations are another challenge, with urban local bodies in India allocating less than 5% of budgets to SWM (Planning Commission, 2014). Few studies have also reflected on how tier-II cities in India lack proper SWM services (Mondal & Mandal, 2024) (Roy, et al., 2022) ; financial constraints and manpower being one of the main reasons (Khajuria et al., 2008; Mani & Singh, 2016; Mondal & Mandal, 2024). Tier-II cities, generally characterized by population ranging from 50,000 to less than 100,000 receive less attention in terms of infrastructural development (Mondal & Mandal, 2024). Despite similar barriers, cities like Kigali, Rwanda, have demonstrated success through strict laws and community engagement (UN Habitat, 2017), while Pune, India, has formalized waste pickers into its system, enhancing recycling rates and livelihoods (Chikarmane, 2012). These examples highlight the need for integrated approaches, public participation, and financial planning, to improve SWM in developing regions.

Studies have highlighted the disproportionate focus on residential waste and commercial waste in SWM, despite its accounting for only 30% of the total municipal waste stream (Sharholy et al., 2008; (CPCB, 2022). According to (Hoornweg & Bhada-Tata, 2012), India generated approximately 1.3 billion tonnes of municipal solid waste (MSW) annually, with an average of 1.2 kg/capita/day. The Central Pollution Control Board (CPCB) reported a total MSW generation of 160038.9 metric tons per day (MT/d) in 2016 (Central Pollution Control Board, 2016). Projections suggest a further increase to 11,95,000 tons per day by 2050 if effective measures are not implemented (Planning Commission, 2014).

Beyond the sheer volume of waste, challenges in SWM arise from factors such as improper management by urban local bodies (ULBs), financial constraints, and lack of public awareness (Mani & Singh, 2016); (Kumar & Agrawal, 2020). Rapid urbanization often strains municipal resources, hindering the development of sustainable waste management infrastructure (Júnior, Pinto, & Câma, 2023). While initiatives like the Swachh Bharat Mission have aimed to address these issues (Ghosh, 2016), their effectiveness has been questioned due to implementation challenges (Krishna, 2017). Waste utilisation in cement plants, coprocessing using of RDF and value creation using waste are reported in literature which will definitely help in reducing the challenges of waste management in cities (Sadhan Kumar Ghosh & Sannidhya Kumar Ghosh, 2021; Moalem, R. M., & Ghosh, S. K., 2024; Liubarskaia, Maria, et al, 2024; Ghosh, S. K., et al, 2022).

1.2 Research Gap

Despite the increasing emphasis on solid waste management (SWM) in India and the implementation of numerous schemes and policies, significant gaps remain in developing effective and sustainable strategies. Studies like those by (Guerrero, Maas, & Hogland, 2013) and (Wilson, Velis, & Cheeseman, 2006) emphasize the role of informal sectors and technical limitations but often overlook critical dimensions such as institutional coordination, financial sustainability, and public participation. Furthermore, the lack of a unified approach that incorporates technological advancements and circular economy principles has limited the scalability and adaptability of existing models. Examples from the OECD countries highlights the various tools in attaining circular economy where the importance of data is underlined (OECD, 2019) to improve the environmental performance review (EPR).

The circular economy (CE) offers a transformative approach to sustainable solid waste management

(SWM) by closing material loops, (Ghosh, S. K., 2020; Ghosh, S. K and S. K. Ghosh, 2023), conserving resources, and reducing environmental impacts (Karak, Bhagat, & Bhattacharya, 2012; MacArthur, 2012). It mitigates greenhouse gas emissions, prevents pollution, and supports biodiversity through recycling, composting, and energy recovery (UNEP, 2019). Economically, CE creates value from waste, generates return of investment (RoI), and generates employment, with the potential for enhanced waste recovery systems (International Labour Organization (ILO), 2018; MarketsandMarkets, 2024). Socially, it formalizes informal waste sectors, improves working conditions, and promotes equity (Adeleke, 2021).

This study addresses these gaps by adopting a holistic approach to develop a sustainable and efficient municipal solid waste management (MSWM) strategy for residential and commercial areas in Cuttack municipality, Odisha, India, with an emphasis on circular economy (CE) principles for Tier-II cities in India. It integrates key dimensions such as public participation, financial viability, and return of investment, offering a framework for comprehensive waste management. By focusing on these interconnected factors, the research not only aims to improve SWM in Cuttack but also provides a replicable model for other Indian Tier-II cities facing similar challenges, thereby contributing to the broader discourse on sustainable urban development.

Through examining waste generation, financial mechanisms, and efficient collection and disposal strategies, this study seeks to bridge the existing research gaps and contribute to the development of comprehensive and sustainable SWM systems aligned with global sustainability goals, such as SDG 12.

2. Study Area

Cuttack city, an oldest city of Odisha, India, was selected as the study area for this research due to its representative nature of the urban waste management challenges prevalent in tier-II cities in India. The city, located between the Mahanadi and Kathajodi Rivers, serves as the administrative centre of Cuttack Municipal Corporation (CMC), with a population of 610,189 (Government of India, 2021) and a land area of 149.16 square kilometres, divided into 59 wards. These wards encompass a wide range of socioeconomic conditions and waste generation patterns, from affluent residential areas to densely populated slums and small-scale commercials. The average household size is estimated to be 4.5 members (Government of India, 2021). With its growing urban infrastructure, Cuttack faces the dual challenge of rapid urbanization and limited municipal resources, which are common across many Indian cities. The selection of Cuttack is further justified by its diverse urban fabric, which includes residential, commercial, and informal settlements, making it an ideal setting to analyse the complexities of municipal solid waste management (MSWM) in a developing country context.

Additionally, Cuttack has seen substantial challenges in waste management due to inadequate infrastructure, financial constraints, and an over-reliance on informal waste management systems, aligning with the broader issues observed in other Indian cities. These issues are compounded by public awareness deficits and the limited capacity of urban local bodies (ULBs) to implement sustainable waste management solutions.

3. Methodology

The study employed a mixed-methods approach, integrating both primary and secondary data collection techniques. Primary data was collected through door-to-door surveys in five selected wards of Cuttack, covering both residential and commercial areas. The wards were selected on basis of population density, socio-economic status and building typologies. The survey focused on key aspects such as respondents' willingness to pay for efficient waste collection, participation in awareness campaigns, and perceptions of current waste management practices. In-depth interviews were conducted with stakeholders, including waste collectors, recyclers, and field workers, to gather qualitative insights into their experiences and the challenges they face in the waste management process.

Secondary data was sourced from the local government body, encompassing land-use data, ward maps, and existing municipal solid waste management plans. Comprehensive Development Plan for Cuttack (IIT Kharagpur, 2006) was taken for reference to understand the city's socio-economic characteristics, demographic profile, building typologies, and waste generation trends. The collected data was analysed to estimate total solid waste generation in two distinct ways: (1) by income distribution, and (2) by the nature of dwelling units. The income-based estimate was used to forecast future waste generation up to 2030, while the dwelling-unit-based estimate focused on waste generation patterns across slums, residential areas, and commercial zones. The evaluation of the waste collection system utilized the estimated waste generation data, along with insights from the primary survey regarding willingness to separate and recycle waste and pay for collection services. This analysis provided an estimate of the potential waste that could be collected through door-to-door services. The waste disposal analysis estimated the quantities of waste suitable for landfilling, composting, and recycling based on the data gathered in the collection stage. Finally, the study developed proposals, recommendations, and potential funding mechanisms for municipal solid waste (MSW) management, drawing on the findings from the primary survey on willingness to pay and cost-benefit analyses of various disposal strategies.

4. Existing SWM practices in Cuttack Municipality

Despite efforts to improve solid waste management (SWM) services, CMC faces significant challenges, such as difficulties in processing tenders for the execution of Integrated Solid Waste Management (ISWM) projects (Panda, 2018). The primary survey revealed several issues regarding the existing SWM situation in Cuttack. First, the provision of waste bins across the city is insufficient, leading to improper waste handling. The total solid waste generated in the Cuttack district, which includes Cuttack city, Athagarh, and Banki, amounts to approximately 227.8 metric tons per day (MT/day) (CTRAN Consulting, 2023). This highlights the substantial waste generation in Cuttack city, exacerbated by its high population density. Furthermore, essential waste management practices such as proper storage, segregation, and door-to-door collection are still not systematically implemented in many parts of the city. Due to narrow alleys and streets, the transportation of waste relies predominantly on wheelbarrows and tractors or trailers, which are old, inefficient and inadequate for managing the growing waste volume. In recent effort to improve the service, the Cuttack Municipal Corporation (CMC) launched the setup of micro system centres (MCCs) and material recovery facilities (MRFs) in different locations for processing of segregated organic waste and recycling of solid waste in 2019 but is not fully operational due to land disputes (Express News Service, 2021) further implying the need of traditional SWM to maintain effectiveness. Additionally, public awareness campaigns on waste segregation at the household level remain minimal, hindering community participation in waste management efforts. These observations underscore the need for a more structured and integrated approach to solid waste management in Cuttack.

4.1 Data Collection

The survey tool used in this study consisted of a set of objective questions focused on socio-economic, physical, environmental aspects and willingness to participate, relevant to the study area. The respondents included household members, retailers, and labourers involved in the municipal solid waste management (MSWM) system. The secondary survey provided crucial data, particularly regarding the environmental aspects of the area, and was obtained from various organizations associated with MSWM. However, the research faced significant constraints, such as the non-availability of specific data and the reluctance of officials to share sensitive information.

Both primary and secondary surveys were instrumental in providing the necessary information to analyse the study area, employing various analytical tools and techniques. Among the 59 wards in Cuttack, five wards—namely Ward No. 31, 38, 39, 40, and 41—were selected as the core study areas (Figure 1), chosen to represent a cross-section of the city's waste management challenges.

4.1.1 Visual survey

During primary survey, the location of dustbins was noted on map, activities of rag pickers, condition of vehicles used for transporting waste, road condition, disposal behaviour of people, waste collection system and nature of dwelling units were observed. As shown in figure 2, the activities of waste management, dustbins, open dumping sites and landfill were recorded.

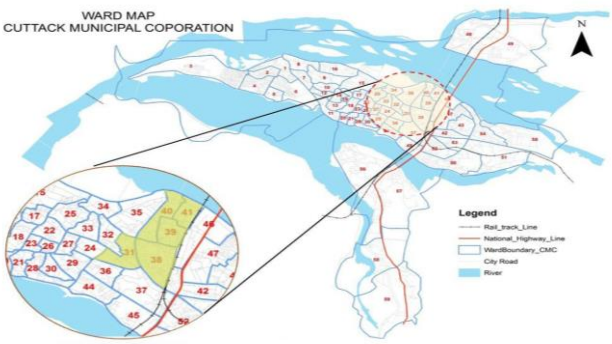


Figure 1 Ward map with selected Wards for survey and data collection. *(Source: (Government of Odisha, 2024)*

Figure 2 Clockwise: a) Manual Measuring of household waste on the spot, b) Existing dumping site at Chakradharpur, c) Collection and transportation of waste, d) The common wheelbarrow used for collection along narrow roads, e) The canal side, f) Common sight of roadside open dumping.
Source: Author

5. Waste Generation

To estimate the amount of waste generation, different parameters were considered based on household types and disposal habits of the households. The following parameters helped in estimating the waste generation: city population, household size, nature of dwelling units and income groups.

5.1 Population at municipal level

The population of the city under CMC has been steadily increasing since 2001. As shown in figure 3, it is expected that the population will rise to 1,060,000 in 2031 (Census of India, 2023). The unavailability of land in the city can be the reason for the decreasing trend in growth rate.

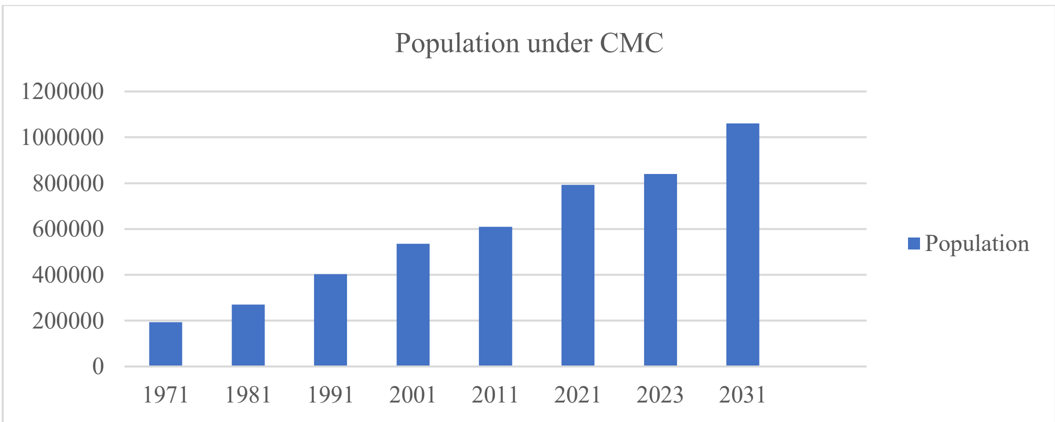


Figure 3 Population Under Cuttack Municipal Corporation.
Source: (Census of India, 2023)

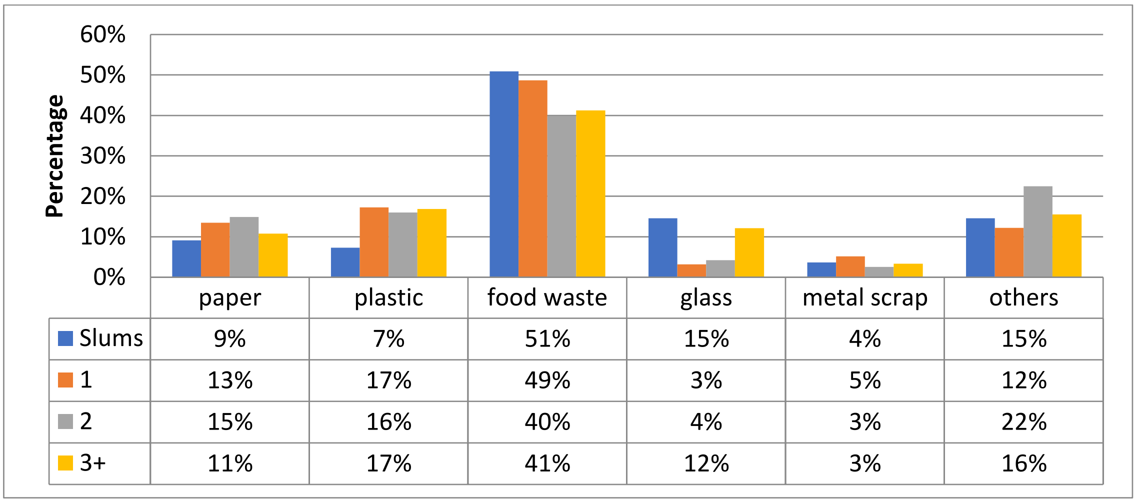
5.2 Residential waste generation based on nature of dwelling units

Calculations were carried out for residential waste generation considering the average weight of waste based on the number of dwelling units in a building in accordance with number of floors and type of buildings. Table 1 shows the estimated average weight of waste generated in terms of building typology and figure 4 shows the composition of different waste generation from different types of dwelling units.

Table 1: Residential waste based on nature of dwelling units in 2021

No. of floors	% of households	Estimated number of buildings	Tot. waste gen. in kg / day
Slums	5.40	6431	2526.46
1storey	78.7	93677	73068.06
2storey	14.0	9269.44	12397.88
Multi storied(3+)	1.93	957.5	2361.83
Total		110334.5	90354.24

Generally, the higher income groups use more packaged materials, which are generally plastic and glass material. While the lower income groups living mostly in slums or one storied building depend on locally available materials, for example, food from local markets and reused materials like plastic, bottles etc, hence the difference. Only food waste generation are mostly same among all groups. Table 2 indicates the average waste generated in each household, which is then multiplied to the number of households to find the total waste generated per day for each income group at city level as tabulated in table 3. In India, the income groups are divided into four categories. To help understand the composition of waste, the contents of various waste generated at the city level were also documented as per the primary survey as shown in Figure 5.



	paper	plastic	food waste	glass	metal scrap	others
Slums	9%	7%	51%	15%	4%	15%
1	13%	17%	49%	3%	5%	12%
2	15%	16%	40%	4%	3%	22%
3+	11%	17%	41%	12%	3%	16%

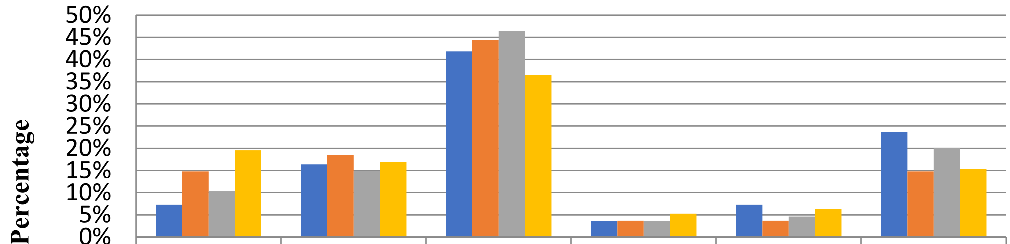
Figure 4 Percentage composition of waste contents at city level based on nature of dwelling units.

Table 2 Average Waste Generation (kg/day/household) based on income group under CMC

Income level (in INR	Average weight kg/day/household)
0-5000	0.46
5000-12500	0.93
12500-25000	1.39
25000 above	1.35

Table 3 Total Waste Generation based on income group for the year 2021 at city level

Income level (in INR)	% of household	No of household	Total waste (kg/day)
0-5000	20.95%	24950	11435.417
5000-12500	60.02%	71478	66372.429
12500-25000	16.20%	19293	26734.586
25000 above	2.83%	3370	4549.500
Total	**100.00%**	**119091**	**109091.931**



	paper	plastic	food waste	glass	metal scrap	others
0-5000	7%	16%	42%	4%	7%	24%
5000-12500	15%	19%	44%	4%	4%	15%
12500-25000	10%	15%	46%	4%	5%	20%
25000 above	20%	17%	37%	5%	6%	15%

Figure 5 Percentage composition of different waste generated at City level based on income groups

It is estimated that the total waste generated on basis of nature of dwelling units is 90354 kg/day while waste generation estimated on basis of income group is 109092 kg/day which gives a difference in gap of 18000 kg/day waste. In the following research, the income-based estimate was used to forecast future waste generation up to 2030, while the dwelling-unit-based estimate focused on waste generation patterns across slums, residential areas, and commercial zones.

Thus, the total waste generation based on income group for the year 2030 was projected to arrive at estimation of 220361 kg/day as shown in table 4 according to the projected household.

Table 4 Projected Waste generation based on income group for the year 2030 at city level

Income level (in INR)	% of household	No of household	Total waste (kg/day)
0-5000	20%	44600	20441.667
5000-12500	46%	102580	95252.857
12500-25000	29%	64670	89614.143
25000 above	5%	11150	15052.500
Total	**100%**	**223000**	**220361.167**

Source: Author (primary survey)

5.3 Commercial waste generation

Total area of commercial land-use of the wards under the study area is estimated to be 0.209 sq.km and the total number of shops within the study area was found to be 492 as per the primary survey.

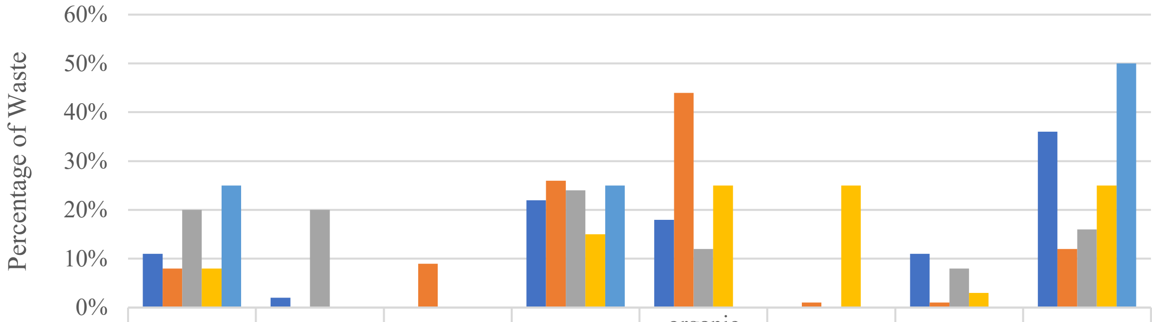
Total Cuttack municipal area = 118.70 sq.km and the percentage of commercial land use in Cuttack is 1.27%. Therefore, 1.51 sq.km of area in Cuttack is of commercial land use.

The number of shops in Cuttack Municipal Area is 3548 and estimated to increase to 6040 shops by 2030. Similar calculations methods were carried out in the case of commercial areas with total number of shops at each ward level and then converted into amount of different waste being generated per day at city municipal level. As shown in table 5, the total waste generated in 2021 was 1325 kg/day and would increase to at least 2100 kg/day by 2030 which is by prediction pertaining to increase in population and shops. From figure 6, it's indicative that plastic and organic waste are more while others waste includes tyres, rubbers, miscellaneous and hazardous waste.

Table 5 Total Waste generated in commercial areas for the year 2021 and 2030 at Ward level

Ward no.	Total waste generated in 2021 (kg/day)	Total waste generated in 2030 (kg/day)
31	328.375	521.3
38	894.75	1420.4
39	73.875	117.3
40	2.5	4.0
41	25.625	40.7
Total	**1325.125**	**2103.6**

Source: Author (primary survey)



	paper	cloth	wood	plastic	organic waste	glass	metal scrap	others
Ward 31	11%	2%	0%	22%	18%	0%	11%	36%
Ward 38	8%	0%	9%	26%	44%	1%	1%	12%
Ward 39	20%	20%	0%	24%	12%	0%	8%	16%
Ward 40	8%	0%	0%	15%	25%	25%	3%	25%
Ward 41	25%	0%	0%	25%	0%	0%	0%	50%

Figure 6 Composition of waste contents at ward level for commercial.
Source: Author (primary survey)

5.4 Other waste generation

As per the Comprehensive Development Planning (CDP) of Cuttack, the other wastes comprise of construction & demolition waste, hospital waste, sweeping waste and hotel/market waste which is constituting around 60% of total waste. This explains that residential waste and commercial waste constitutes 40% of total waste.

Taking this simple calculation from table 3 and table 5, the total of residential and commercial waste generated in 2021 at city level is 109092+1325.12 = 1,10,417.12 kg/day, i.e. 110.42 MT/day. And other waste would be 165.63 MT/day. So, the total waste generated at City municipal level in 2021 is 276.05 MT/day.

Similarly, the projected total residential waste and commercial waste generation in 2030 as per table 4 and table 5 is 223 MT/day. Assuming the percentage of other waste to be constant till 2030, then the amount of other waste generation is estimated to be 334.5 MT/day and the Total Waste generated is estimated to approximately 557.5 MT/day.

6. Waste Collection

In secondary survey, an interaction with municipal staffs and other stakeholders helped to find the characteristics of the waste collection system in Cuttack which included number of permanent staffs, temporary staffs and vehicles used for transportation. The final dumping site is located at Chakradharpur which is 25km from Cuttack Municipal Corporation (CMC) office. The location of dustbins, route of transportation and collection point were also noted through primary surveys.
According to CMC, there are more than 900 permanent staff, 150 temporary staff and 15 trucks (7.5 cu.m), 55 tractors (2.8 cu.m), 300 wheelbarrows used for the solid waste collection services. According to the current situation, waste segregation is not practiced regularly, and some waste are dumped in open which starts to stagnate and creates odours in the neighbourhood. For SWM services, the Municipality does not impose any taxes on households. According to the garbage collectors they receive a daily wage of about ₹80. While most budget is spent on other infrastructure and amenities, there's financial constraints to run efficient SWM activities. Therefore, the following discussion helps in deriving the estimate fund that could be collected from public participation.

7. Discussion

7.1 Willingness to separate and recycle: -

From survey it was found that locals were ready to help the government and non-government organization (NGO) in form of collection system. The data in figure 7 shows the number of people willing to separate and recycle based on the type of building people are living in.

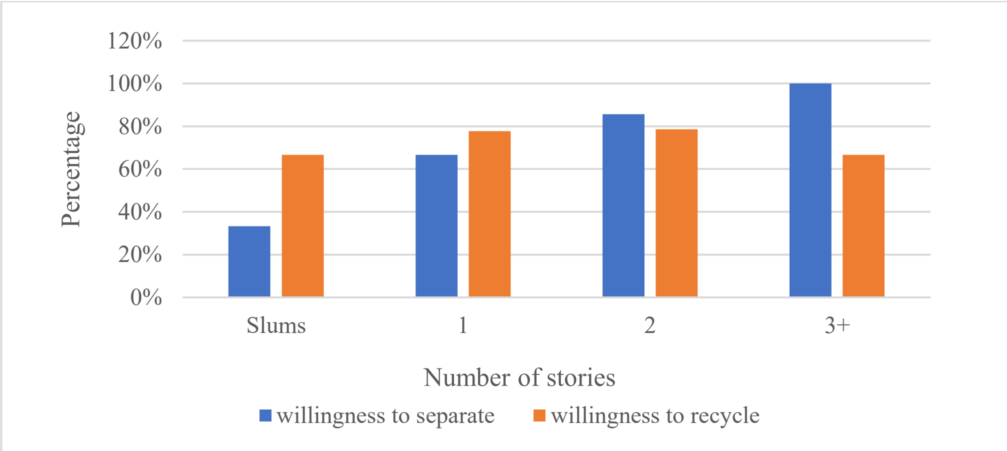


Figure 7 Number of people willing to separate and recycle.
Source: Author (primary survey)

7.2 Findings

It is observed, a greater number of households belonging to buildings with more than one storey or alternatively households belonging to higher income groups is willing to separate.

At the city level, average 71% of household willing to separate was estimated whereas, the average percentage of household willing to recycle was estimated as 72%.

Thus, considering the content of existing waste and the willingness of people to separate and recycle, the amount of waste could be categorized into three types for daily disposal, namely, (a) Landfill waste, (b) Compost waste and (c) Recyclable waste as shown in table 6 and 7. Based on above analysis, these wastes were estimated for the year 2030 at the city level indicating the amount of waste that can be landfilled, composted and recycled.

Table 6 Amount of landfill waste and compost waste for daily disposal for Cuttack, 2030 (in kg/day)

CMC 2030	**(A) Landfill**						**(B) Compost**
Sources	**Kitchen waste**	**Paper**	**Plastic**	**Glass**	**Metals**	**Others**	**Kitchen waste**
Slums	545	94	75	150	38	150	1341
Residential	28288	7820	10431	2210	2837	10994	69675
Commercial	137	737	51	1519	2310	1583	336
Others	-	-	-	-	-	83600	-
Construction	-	-	-	-	-	141000	-
Total waste	28969	8651	10557	3879	5185	237326	71353
Grand total	**294568**						**71353**

Table 7 Amount of recyclable waste for daily disposal for Cuttack, 2030 (in kg/day)

CMC 2030	**(C) Recyclable waste**			
Sources	**Paper**	**Plastic**	**Glass**	**Metals**
Slums	243	194	389	97
Residential	20226	26980	5716	7338
Commercial	1907	131	3928	5976
Others	-	-	-	-
Construction	-	-	-	-
Total waste	22376	27306	10032	13411
Grand total	**73125**			

7.3 Willingness to pay

Governance needs funding to leverage SWM service for Cuttack city (Mani & Singh, 2016). Public participation for urban governance can be effective if the local people participate to support in the form of fund. Participation of NGOs especially for waste collection plays a significant role for proper solid waste management, if proper funds are arranged to facilitate the system (Chatri & Aziz, 2012). As per primary survey, figure 8 indicates the willingness to pay by the locals for door-to-door collection system, odour-free surroundings and street clean city and has been analysed to estimate possible funds to utilize for effective SWM system.

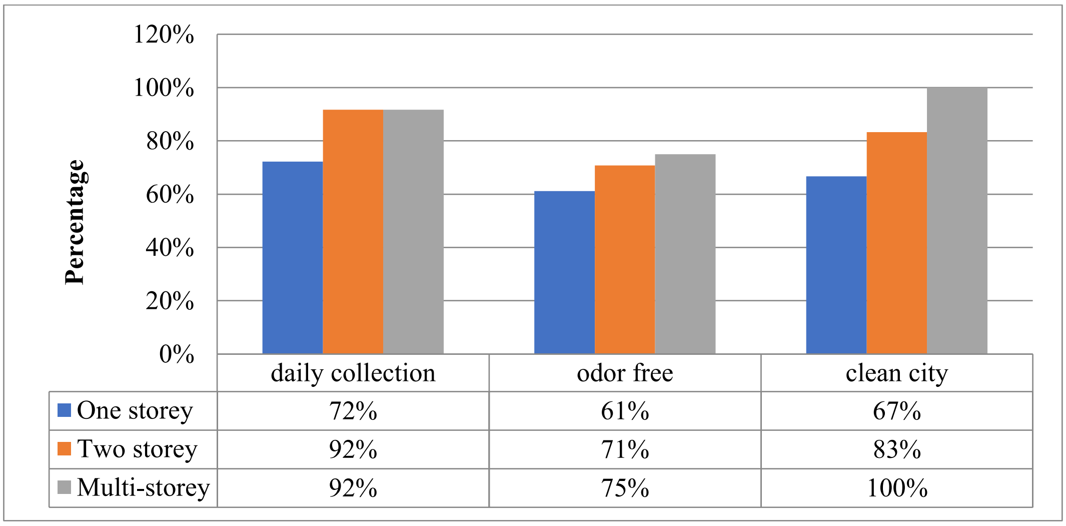


Figure 8 Percentage of people willing to pay for MSW activities.
Source: Author (primary survey)

Table 8 shows the categories of dwelling units where households are willing to pay an average price/month for different activities. The slum dwellers were not approached due to their economic constraints. The average user charge for daily collection was ₹10/month/family, then the annual charge would be ₹120/month/family. This data helped to find the Gross amount of money that could be collected through all the households as well as the shops in Cuttack city. Table 9 shows how much money could be collected for door-to-door collection.

Table 8 Average price/month for different SWM services

No. of floors	For daily collection (in ₹)	For odour free area (in ₹)	For street clean city (in ₹)
1	6.0	8.4	7.7
2	7.00	9.56	7.86
Multi-storied	7.2	10.6	7.6

Source: Author (primary survey)

Table 9 Total collection (in INR/year)

No. of floors	₹/year/building or shop	No. of buildings/ shops (estimated)	Cuttack (at city level) in ₹
One	120	93677	₹11241240
Two	216	9269	₹2002200
Multi-storied	288	957.5	₹275760
Commercial	120	3533	₹423960
Amount to be collected for door-to-door waste collection per year			₹ 1,39,43,160

Source: Author (primary survey)

8. Door-to-door waste collection strategy

Calculations were performed over the data at the ward levels to evaluate the estimation for various waste management actions. As previously mentioned, this study limits to findings for the ward numbers 31, 38, 39, 40 and 41. Based on data collected, similar computations can be performed for other wards to obtain desired results.

Labor requirement: In the current situation, factors such as the number of buildings, the wheelbarrow's speed, the amount of time needed for loading and unloading, etc. were considered when calculating the number of workers needed to collect the waste. With the working hours of 7 a.m. to 11 a.m. (4 hours/day), one can determine the number of labours needed for each ward. Table 10 gives the break-ups of the number of labourers estimated for each ward based on time to collect the waste.

Table 10 Estimate number of labours of each ward based on time

Time taken to collect	ward 31	ward 38	ward 39	ward 40	ward 41
for Slums (in minutes)	3.6	4.8	7.2	6.0	3.6
for 1 storied (in minutes)	3224.4	3071.0	2944.0	1186.3	1383.6
for 2 stories (in minutes)	319.1	303.9	291.3	117.4	136.7
for multi-storied (in minutes)	33.0	31.4	30.1	12.1	14.0
Total Time (in minutes)	**3580.0**	**3411.1**	**3272.6**	**1321.8**	**1537.9**
Converted into Hours	59.7=60	56.9=57	54.5=55	22.0	25.6=25
Estimated number of Laborers	**60/4 = 15**	**57/4 = 14**	**55/ 4 = 14**	**22/4 = 6**	**25/4 = 6**

Source: Author (primary survey)

Table 11 Total waste to be collected at ward level (in kg/day)

Types of waste	Ward 31	Ward 38	Ward 39	Ward 40	Ward 41
Landfill waste	1946	2189	2060	538	963
Compost waste	963	376	948	268	441
Recyclable waste	997	1241	1060	240	239

Source: Author (primary survey)

Cart/wheelbarrows requirement: Pertaining to narrow lanes in the city, carts[1] are considered more suitable to carry waste through door-to-door and transfer to the lorry that takes for final disposal to landfill. Table 11 estimates the amount of waste to be collected from door-to-door from each ward based on the findings from Section 7, and Table 12 computes the number of carts required for each ward.

Table 12 Estimate of number of carts required to collect different waste from each ward

Type of waste	Ward 25	Ward 31	Ward 32	Ward 33	Ward 34
Landfill waste	19	22	21	5	10
Compost waste	10	4	9	3	4
Recyclable waste	10	12	11	2	2
Total carts	**39**	**38**	**41**	**10**	**16**

9. Waste Disposal

Existing scenario: The secondary survey helped to list out the scenario of waste disposal by interviewing the CMC staffs. According to the visual survey, it was noted than only 60% of waste collection is achieved, the dumping was the only method, segregation of waste is not practiced, rag pickers collect few plastics (bottles and bags) and sell them at ₹10/kg.

Estimate for Sanitary landfill area: According to the estimation, the standard density of waste at landfill after compaction is taken as 600 kg/cu.m.. The volume of daily landfill waste is estimated as 372cu.m. Considering 20 years from now, total volume of landfill waste is estimated as 2,715,600cu.m. Assuming the depth of the land fill = 4m (considering a safety of 2 metre from ground water table to avoid leachate contamination); area for landfill is estimated as 678900 sq.mts. ((For e.g. (824 x 824) sq. mts.) or 167 acres

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1. The capacity of one cart is 6 cubic feet and can carry 100 kg of municipal solid waste when fully loaded approx. The site has been proposed as per Cuttack CDP 2009, hence, not considered as part of the research.

Estimates on area requirement for compost plants: According to the survey, the volume of a single compost pit is 486 cu.ft [2]. The density of food waste, when compacted, was found to be 1029 kg/cu.m i.e., 14163 kg [2] of compost waste can be composted in 486 cu.ft pit. From section 7.2, it is estimated that by 2030 the total compost waste would be 71353 kg/day, leading to requirement of 5 pits to compost per day. Assuming the decomposing of waste to be 30 days, the total number of pits required will be 150. The total area for compost plant including the area of all pits and area for drying the composted materials which is 1.5 times the area of total pits = 18 x 9 x 150 x 1.5 = 36,450 square feet = 0.83 acres of land.

Estimates on recyclable waste: According to the analysis from section 7, the total recyclable waste including – paper, plastic, glass, and metals would be 73125 kg/day waste estimated for 2030 at city. Waste segregation centres should be constructed at each ward considering the quantity of recyclable waste.

10. Proposals and Return of Investment

Fund collection by municipalities: Based on the analysis from sections 7, the total money that the Municipality can collect is estimated as ₹ 1.39 crore[i]/year. These can be used for street cleaning, collection from community bins and mini ports, odour-free areas, transfer of waste, and landfilling. Recently, CMC has advertised the tender for the hiring of battery-operated vehicles (BOV) for door-to-door collection (CMC, 2022), therefore the revenue may be used for such practices too.

Cost-benefit analysis on composting: Considering the average selling price of compost to be ₹2000/ton, construction of composting plant to be ₹1500000, implementation and machinery to be ₹400000, and other costs to be ₹650000, the revenue generation is estimated as ₹1104000 for 30 days which proves composting to be the most profitable operation. With recent launch of Micro-composting Centres and material recovery facilities (CMC Cuttack, 2024), this revenue can be applicable to keep these facilities operational.

Costs benefit analysis on Recycling: Considering the average selling price of each recycled material, the total revenue generation could be estimated for the year 2030 as follows –

Recycled paper (at INR 7.5/kg)	= INR 46,833,150/year
Recycled plastic (at INR 1.2/kg)	= INR 9,599,208/year
Recycled glass (at INR 3.7/kg)	= INR 10,556,859/year
Recycled metals (at INR 21.8/kg)	= INR 68,883,749/year

11. Conclusion

The amount of solid waste generated in Cuttack city is expected to increase dramatically in coming years as the city expands in linear pattern along with population increase. The objective of this research was to assess the quantity of solid waste generated and its proportion to the collection and disposal. However, this study found that most of the areas do not have proper infrastructure, lacks human resources, and often faces financial constraints. This research underscores the critical role of public awareness, community participation, and government-led initiatives in achieving effective Municipal Solid Waste Management (MSWM) within the framework of a circular economy in Tier-II city. Also, the study found that while the Swachh Bharat Mission has been a significant initiative by the government of India, its practical implementation remains hampered by inconsistent public participation and a lack of comprehensive awareness. Cuttack city is one of the oldest cities of Odisha and surrounded by two rivers on either side, making it a compact city with higher population density. The study focussed on the wards number 31, 38, 39, 40 and 41 as per the diversity in population density, building typologies, living lifestyle, bordering river, closeness to the railway line and centric to the city, which could represent similarity at city level. Despite these challenges, the research highlights the tangible and intangible benefits of proper waste management, including door-to-door collection, segregation of waste from home, collection of waste, revenue generation through disposal methods like composting and recycling, and participation of non-government organizations. The key effort has been taken to align with the principles of a circular economy by focusing on public willingness to contribute monetarily and participate in separation of waste at home, which helps in generating the funds for composting and recycling at initial stage. These practices would directly contribute to marketing the compost and recycled products to generate profit by selling them at market rate. The return of investment through such practices can be used to purchase new vehicles, allot more human resources and build better infrastructure for collecting wastes. By revenue generation, Cuttack city can transition towards circular economy, fostering sustainable development, reducing waste, and contributing to a cleaner, healthier environment, ultimately inviting for newer technology and larger workforce.

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2. Volume of the pit (LxBxH) = 18x9x3 cubic feet (cu.ft.)

Additionally, a comprehensive action should be taken by municipal authorities to stop illegal dumping of waste, ensure separation of waste at home, implement more sustainable urban waste management strategies.

This research methodology and findings from this study could be applied to other Indian cities like Tier-II category to develop more effective MSWM strategies, in line with the principles of a circular economy.

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References

Adeleke, O. A. (2021). Towards sustainability in municipal solid waste management in South Africa: a survey of challenges and prospects. *Transactions of the Royal Society of South Africa, 76*(1), 53-66. doi:https://doi.org/10.1080/0035919X.2020.1858366

Census of India. (2023, December). Retrieved from Census2011: https://www.census2011.co.in

Central Pollution Control Board. (2016). *Status report on Municipal Solid Waste Management.* New Delhi: Government of India.

Chatri, A. K., & Aziz, A. (2012). *Public Private Partnerships in Municipal Solid Waste Management:Potential and Strategies.* Athena Infonomics India Pvt. Ltd. Retrieved 04 2024, from https://www.nswai.org/docs/ReportPPPMunicipalSolidWasteManagement270812.pdf

Chikarmane, P. (2012, July). Integrating Waste Pickers into Municipal Solid Waste Management in Pune, India. *Women in Informal Employment Globalizing and Organizing*, p. 12.

CMC. (2022, November 22). *CMC Cuttack.* Retrieved from QUOTATION / TENDER CALL NOTICE : cmccuttack.odisha.gov.in

CMC Cuttack. (2024, February). *Instagram*. Retrieved from Cuttack Municipal Corporation: https://www.instagram.com/cmc_cuttack/reel/C3nCWJeoxho/?locale=en_gb

CPCB. (2022). *Annual Report on Solid Waste Management 2020-2021.* New Delhi: Central Pollution Control Board.

CTRAN Consulting. (2023). *Environmental Synthesis Report of Odisha.* Forest, Environment and Climate Change Department, Government of Odisha. Retrieved 2024, from https://forest.odisha.gov.in/

Dipeolu, A. A., Akpa, O. M., & Fadamiro, J. A. (2020). Mitigating Environmental Sustainability Challenges and Enhancing Health in Urban Communities: The Multi-functionality of Green Infrastructure. *Journal of Contemporary Urban Affairs, 4*(1), 33-46. doi:https://doi.org/10.25034/ijcua.2020.v4n1-4

Esmaeilian, B., Wang, B., Lewis, K., Duarte, F., Ratti, C., & Behdad, S. (2018). The future of waste management in smart and sustainable cities:. *Waste Management, 81*, 177-195. doi:https://doi.org/10.1016/j.wasman.2018.09.047

Ghosh, S. K. (2016). Swachhaa Bharat Mission (SBM) – A Paradigm Shift in Waste Management and Cleanliness in India. *Procedia Environmental Sciences, 35*, 15-27. doi:https://doi.org/10.1016/j.proenv.2016.07.002

Government of India. (2021). *Census of India 2011 - Odisha.* Retrieved from https://censusindia.gov.in/nada/index.php/catalog/926

Government of Odisha. (2024). *Site Map*. Retrieved from CMC Cuttack Odisha: https://cmccuttack.odisha.gov.in/?page_id=2876

Guerrero, L. A., Maas, G., & Hogland, W. (2013, January). Solid waste management challenges for cities in developing countries. *Waste Management, 33*(1), 220-232. doi:https://doi.org/10.1016/j.wasman.2012.09.008

Hoornweg, D., & Bhada-Tata, P. (2012). *What a Waste : A Global Review of Solid Waste Management.* Washington, DC: World Bank. Retrieved February 2022, from https://openknowledge.worldbank.org/handle/10986/17388

IIT Kharagpur. (2006). *Comprehensive Development Plan.*

International Labour Organization (ILO). (2018). *World Employment and Social Outlook 2018: Greening with jobs.* Geneva: International Labour Office.

Júnior, N. A., Pinto, F. R., & Câma, S. F. (2023, December). Analysis and Proposal for Actors' Roles in Solid Waste Management in the City of Fortaleza (Brazil). *The Journal of Solid Waste Technology and Management, 49*, 340-358. doi:https://doi.org/10.5276/jswtm/iswmaw/494/2023.340

Karak, T., Bhagat, R., & Bhattacharya, P. (2012). Municipal Solid Waste Generation, Composition, and Management: The World Scenario. *Critical Reviews in Environmental Science and Technology, 42*(15), 1509-1630. doi:https://doi.org/10.1080/10643389.2011.569871

Klundert, A. v., & Anschütz, J. (2001). *Integrated Sustainable Waste Management - the Concept.* (A. Scheinberg, Ed.) Gouda, The Netherlands: WASTE. Retrieved 2024, from https://www.ircwash.org/resources/integrated-sustainable-waste-management-concept

Ghosh, S. K., (2020), Circular Economy: Global Perspective (Ed. Book), Springer Nature Singapore Pte Ltd. 2020, https://doi.org/10.1007/978-981-15-1052-6

Ghosh, Sadhan Kumar, and Sannidhya Kumar Ghosh. "Circular Economy Catalysing Decarbonization." Circular Economy Adoption: Catalysing Decarbonisation Through Policy

Instruments. Singapore: Springer Nature Singapore, 2023. 3-33. DOI. 10.1007/978-981-99-4803-1_1

Krishna, G. (2017, April 29). Why Urban Waste Continues to Follow the Path of Least Resistance. *Economic and Political Weekly, 52*(17), 95-101. Retrieved 2022, from https://www.jstor.org/stable/26695972

Krishna, G. (2017, April 29). Why Urban Waste Continues to Follow the Path of Least Resistance. *Economic and Political Weekly, 52*(17), 95-101. Retrieved 2024, from https://www.jstor.org/stable/26695972

Kumar, A., & Agrawal, A. (2020). Recent trends in solid waste management status, challenges,. *Current Research in Environmental Sustainability, 2*, 7-19. doi:http://dx.doi.org/10.1016/j.crsust.2020.100011

Liubarskaia, Maria ; Ghosh, Sadhan Kumar; Klunko, Natalia ; Melnikov,Vladislav (2024) ; Implementation of projects for using RDF as a tool for increasing energy and resource efficiency of enterprises, The Journal of Solid Waste Technology and Management, Volume 50, Number 4, November 2024, pp. 640-653(14); https://doi.org/10.5276/jswtm/iswmaw/50S1/2024.640

MacArthur, E. (2012, January). Towards the Circular Economy: Economic and business rationale for an accelerated transition. Green Policy Platform . Retrieved November 2024, from https://www.greenpolicyplatform.org/research/towards-circular-economy-economic-and-business-rationale-accelerated-transition

Mani, S., & Singh, S. (2016). Sustainable Municipal Solid Waste Management in India: A Policy Agenda. (S. K. Ghosh, Ed.) *Procedia Environmental Sciences, 35*, 150-157. doi:https://doi.org/10.1016/j.proenv.2016.07.064

MarketsandMarkets. (2024, April 08). Waste Management Market by Waste Type, Disposal, Source & Region - Global Forecast to 2029. p. 293. Retrieved from https://www.giiresearch.com/report/mama1465226-waste-management-market-by-waste-type-disposal.html

Ministry of Housing and Urban Affairs. (2019). *Swachhata Sandesh Newsletter.* Government of India.

Moalem, R. M., & Ghosh, S. K. (2024). Value Creation from Waste: Roles and interface between the Informal and Formal waste Sectors in India and Denmark in a just circular transition. The Journal of Solid Waste Technology and Management, 50(4), 711-724. doi: https://doi.org/10.5276/jswtm/iswmaw/50S1/2024.711

Mohan, R., & Dasgupta, S. (2005, January). The twenty first century: Asia becomes Urban. *Economic and Political Weekly, 40*(03), 213-223. Retrieved August 2024, from https://www.jstor.org/stable/4416078

Mondal, S., & Mandal, B. (2024). Assessment of urban solid waste management in a Class II Indian city using. *Waste Management Bulletin*, 74-92. doi:https://doi.org/10.1016/j.wmb.2023.09.003

OECD. (2019). *Waste Management and the Circular Economy in Selected OECD Countries: Evidence from.* Paris: OECD Publishing. doi:https://doi.org/10.1787/9789264309395-en

Paes, M. d. (2021). Transition to circular economy in Brazil: A look at the municipal solid waste management in the state of São Paulo. *Management Decision, 59*(8), 1827-1840. doi:https://doi.org/10.1108/MD-09-2018-1053

Panda, A. (2018, December 14). Cuttack's garbage segregation proposal goes waste. Odisha, India: The New Indian Express. Retrieved September 2024, from https://www.newindianexpress.com/states/odisha/2018/Dec/14/millennium-citys-garbage-segregation-proposal-goes-waste-1911404.html

Planning Commission. (2014). *Report of the Task Force on Waste to Energy.* New Delhi: Planning Commission. Retrieved 2024

Research, C. (2022). *Tier-II Cities: Coming of Age.* Inductus GCC. Retrieved from https://inductusgcc.com/wp-content/uploads/2024/09/The-Rise-of-GCCs-in-Indias-Tier-2-Cities.pdf

Roy, M., Mukherjee, D., Bhaduri, S. K., Nandi, S., Ghosh, R., & Yogi, R. (2022, November). Municipal Solid Waste Estimation and Management - Challenges and Lessons from Regional. *The Journal of Solid Waste Technology and Management, 48*(4). doi:https://doi.org/10.5276/JSWTM/2022.532

Sadhan Kumar Ghosh, Sannidhya Kumar Ghosh (2021), Conceptualising Circular Economy, Circular Economy: Recent Trends in Global Perspective (Ed. Book), Springer Nature Singapore Pte Ltd, 2021, pp 3-26, doi: https://doi.org/10.1007/978-981-16-0913-8_1

Singh, N. (2024). *THE RISE OF GLOBAL CAPABILITY CENTERS IN INDIA'S TIER-2 CITIES-AN ANLYSIS.* Inductus Global Capability Centres (GCC). Retrieved 2025, from https://inductusgcc.com/global-capability-centers-gccs-in-india-the-rise-of-tier-2-cities/#:~:text=Tier%2D2%20cities%20such%20as,the%20unique%20advantages%20they%20offer.

UN Habitat. (2017). *Kigali, Rwanda: A model of cleanliness and orderliness in Africa.* UN Habitat.

UNEP. (2019). *Global Environment Outlook – GEO-6: Healthy Planet, Healthy People.* Cambridge University Press. doi:https://doi.org/10.1017/9781108627146

Wilson, D. C., Velis, C., & Cheeseman, C. (2006, December). Role of informal sector recycling in waste management in developing countries. *Habitat International, 30*(4), 797-808. doi:https://doi.org/10.1016/j.habitatint.2005.09.005

[i] *One crore equals 10 million*

Electricity generation from pure lactic acid and cottage cheese whey in a Microbial fuel cell using Shewanella Putrefaciens MTCC 8104: Mathematical modelling and Experimental studies

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ABSTRACT

Mathematical models of microbial fuel cells (MFCs), developed so far, often rely on simplified assumptions regarding microbial growth kinetics, substrate utilization, and extracellular electron transfer. Such oversimplifications limit their predictive accuracy and applicability to real waste-derived substrates, which typically contain inhibitory compounds and variable organic compositions. To address these shortcomings, this study presents a comprehensive mathematical model of a mediator-less MFC employing Shewanella putrefaciens MTCC 8104 as suspended culture in anode chamber. The performance of MFCs, run on pure lactic acid and cottage cheese whey, was systematically compared. The model integrates substrate degradation and microbial growth kinetics with electron transfer mechanisms to accurately predict bioelectricity generation. Experimental validation demonstrated strong agreement between model predictions and measured data, with root mean square error (RMSE) and normalized RMSE (NRMSE) values remaining well below 10% for both current and power density, confirming the robustness of the model. Results revealed that the pure lactic acid–fed MFC achieved maximum power and current densities of 1147 mW/m² and 2.21 A/m², respectively. In comparison, the cottage cheese whey–fed MFC exhibited lower values—287.48 mW/m² and 0.92 A/m²—representing 25.1% and 41.6% reductions, respectively. While performance with whey was lower, its use offers substantial economic and environmental benefits, as it valorizes an abundantly available agro-industrial by-product otherwise treated as waste. This dual advantage highlights the promise of integrating renewable energy recovery with sustainable waste management. The validated mathematical model provides a reliable framework for scaling up MFCs operated with similar substrates.

Keywords: Microbial fuel cell, Shewanella putrefaciens, mathematical modeling, waste valorization, dairy wastewater, sustainable energy, extracellular electron transfer, circular economy.

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Introduction

The increasing global demand for sustainable energy solutions has intensified research into bio-electrochemical systems, particularly microbial fuel cells (MFCs), which offer the dual advantage of renewable electricity generation and organic waste remediation [Ojha et al., 2024; Feng et al., 2024; Chandra et al.,2025]. Among various MFC configurations, mediator-less systems utilizing exo-electrogenic bacteria like *Shewanella putrefaciens* have gained significant attention due to their inherent ability to transfer electrons directly to electrodes without requiring chemical mediators [Kim et al.,2002]. This study focuses on developing a comprehensive mathematical model for a MFC employing *S. putrefaciens* MTCC 8104 in suspended culture, with particular emphasis on comparing pure lactic acid and lactic acid present in cottage cheese whey as substrates.

Lactic acid has emerged as an excellent substrate for MFCs due to its efficient oxidation by electroactive bacteria [Ateş et al.,2024; Casallas-Ojeda et al.,2024; Segundo et al.,2025; Kanellos et al.,2024]. While studies have been extensively investigated pure lactic acid in MFC systems, the utilization of waste-derived lactic acid—particularly from dairy byproducts like cottage cheese whey—remains relatively unexplored. Cottage cheese whey, a protein-rich dairy effluent, contains significant amounts of lactic acid but is often discarded as waste, posing environmental challenges due to its high organic load [Rincón-Catalán et al.,2022]. Previous studies have shown that MFCs using dairy wastewater or whey-based substrates deliver lower absolute performance compared to pure substrates, but they offer distinct advantages in terms of cost reduction, waste valorization, and environmental benefits [Ghaly et al., 2005]. Given that CCW is abundantly generated as an agro-industrial by-product and poses environmental challenges due to its high organic load, its valorization as an MFC substrate provides both ecological and economic incentives.

Mathematical modeling plays a pivotal role in understanding and optimizing MFC performance by capturing the interactions between microbial kinetics, substrate degradation, and electron transfer. Earlier models are largely empirical, focusing on polarization curve fitting, which allow quick performance estimation but lack mechanistic insight [Zeng et al., 2010]. Although models incorporating Monod-type kinetic models improve predictive power by linking microbial growth to substrate consumption, they often overlook extracellular electron transfer and associated energy losses [Picioreanu et al., 2007]. Electrochemical models integrating Nernst–Monod formulations provide a better framework by including overpotentials and ohmic losses [Seyezhai and Mathur., 2011]. However, they are often unable to incorporate substrate inhibition, variability in composition, and competing reactions, which are critical when dealing with complex effluents [Marcus et al., 2007]. Thus, the need remains for a comprehensive mathematical framework that bridges these gaps and provides robust predictive accuracy across both pure and waste-based substrates.

Against this backdrop, the present study develops and validates a comprehensive mathematical model of a mediator-less MFC operated with Shewanella putrefaciens MTCC 8104 as suspended culture. The framework is termed novel because, unlike earlier models, based on Monod kinetics or Nernst–Monod formulations, validated with simple synthetic substrates, the present model integrates microbial growth kinetics, substrate degradation, and extracellular electron transfer into a single predictive framework. Importantly, it has been validated not only with pure lactic acid but also with cottage cheese whey, a complex agro-industrial effluent containing proteins, fats, and lactose that introduce inhibitory effects. By incorporating substrate inhibition and electron recovery efficiency factors, the model provides a more realistic representation of mediator-less MFC performance under both controlled and real waste conditions. By systematically comparing MFC performance with pure lactic acid and CCW, the study not only elucidates substrate-specific microbial kinetics and electron transfer mechanisms but also addresses practical considerations of using real waste streams for sustainable bioelectricity generation.

Materials and Methods:

Chemicals and glassware

All chemicals, as mentioned in the experimental section were purchased from Merck. Glassware (Centrifuge tubes, conical flasks, Milli- and Micropipettes, Micropipette tips) were from Tarson and Borosil.

Analytical Instruments

UV-VIS spectrophotometer (K.Roy SN: YA02151904272) was used to determine the optical density and absorbance of suspension and solution, wherever required.

Microorganisms

The electro-active bacterial strain, *Shewanella putrefaciens* MTCC 8104, procured from Microbial Type Culture Collection (MTCC), Chandigarh, India was used in the anode chamber of the MFC.

Carbon substrates for *Shewanella Putrefaciens MTCC 8104(S.Putrefaciens)*

This study utilized (1) lactic acid-rich cottage cheese whey (MFC-CCW: 3 g/L lactic acid in CCW); (3) pure lactic acid (MFC-Lac: 3g/L lactic acid) as carbon substrates for the microorganism in the anode chamber. Cottage cheese whey was collected from a local shop of dairy products in Lake Gardens, Kolkata, India. The concentration of lactic acid in the whey, as quantified using a standard protocol, was 5.14g/L [Borshchevskaya et al.,2016]. The spectrophotometer was also needed for this analysis, as described in the supplementary section.

Experimental Set-Up:

The experimental setup utilized a concentric cylindrical two-chamber MFC design with unique construction features. The anode compartment consisted of an earthen pot (55 mm diameter × 75 mm length) containing 100 mL of anolyte (filled to 42 mm height), which was concentrically positioned within a larger PET cathode chamber (100 mm diameter) holding 250 mL of catholyte (45.5 mm height). This innovative configuration employed the porous earthen pot wall to serve dual functions: as both the anode container and a natural proton exchange membrane, thereby eliminating the requirement for a separate membrane component. Both chambers were fitted with 20 × 20 mm carbon cloth electrodes (anode immersed in anolyte and cathode in catholyte), interconnected via a 1 kΩ external resistor. This compact design effectively leveraged the inherent ion exchange properties of earthenware while maintaining a simple and functional architecture.

Growth Kinetics of *S.Putrefaciens* on lactic acid and CCW:

The growth kinetics of *S.Putrefaciens* were investigated using both pure lactic acid and cottage cheese whey (CCW) as carbon sources through anaerobic batch experiments in 250 ml conical flasks bottles containing M-9 minimal salt medium supplemented with each substrate, with triplicate cultures monitored via regular OD600 measurements and spectrophotometer analysis of lactic acid consumption. Growth parameters were derived by Monod kinetics to the exponential phase data, while accounting for potential substrate inhibition in lactic acid and CCW, and biomass yield coefficients calculated from substrate-to-biomass conversion ratios. The comparative kinetic analysis between pure and whey-derived lactic acid systems, provided essential physiological parameters for predicting the organism's performance in mediator-less MFC applications.

Anolyte and Catholyte of MFC

Anolyte: 10x M-9 minimal salt media is used the anode chamber of MFC. The composition of 10x M-9 medium is: 5 g/l NaOH, 5 g/l NH_4Cl, 75 g/l K_2HPO_4, 30 g/l KH_2PO_4, 10 g/l $MgSO_4$, 10 g/l $CaCl_2$. The pH was adjusted to 7.0.

Catholyte: The cathodic chamber of the MFC was filled with 25mM phosphate buffer solution (2.678 kg/L K_2HPO_4 and 1.310 kg/L KH_2PO_4, adjusted to pH of 7) [Watson and Logan;2010]. Oxygen was supplied to the catholyte, i.e., the medium in the cathode, by injecting air into the catholyte using an air pump at a flow rate of 8×10^{-4} L/min till the steady-state concentration of 7.26 mg/L was attained [Esfandyari et al.,2017].

Operation of MFC

Anaerobic atmosphere was maintained in the anode chamber by purging with nitrogen at the start-up. The gas inlet and outlet of the anode chamber were sealed to maintain anaerobic condition. All the MFCs were run for 240h. The performance of MFCs were assessed by measuring voltage and current using a multi-meter across the external resistance every 24 h interval. The experimental setup includes a Microbial fuel cell is shown in Figure 1.a. A flow chart of the methodology is illustrated in figure 1.b.

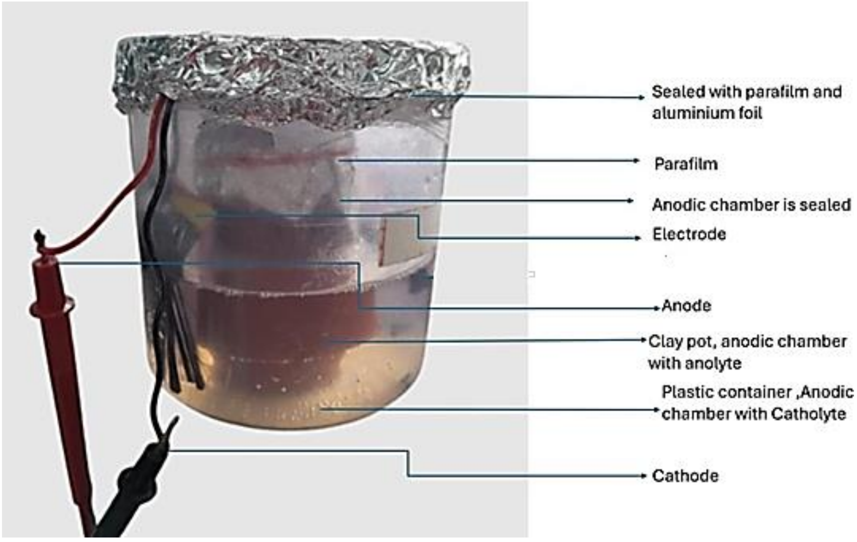


Figure 1.a: Microbial fuel cell experimental setup

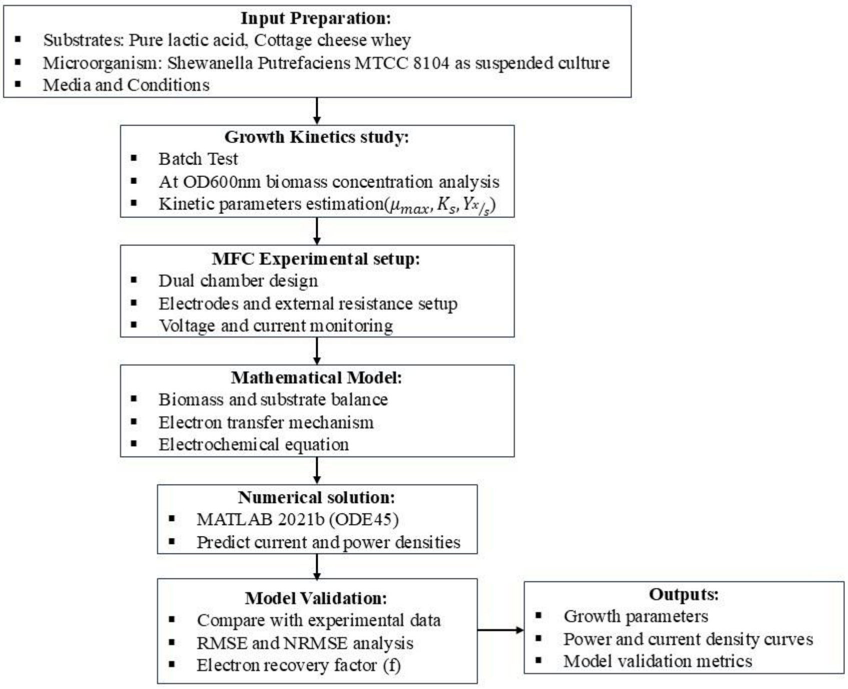


Figure 1b: Flow chart of methodology

Theoretical Analysis

The growth kinetics of *S.Putrefaciens* on lactic acid and CCW in the non-inhibitory regime follows Monod model. These are as follows:

$$\mu_{Lac} = \frac{\mu_{max,Lac} \times C_{Lac}}{k_{S,Lac} + C_{Lac}} \quad (1)$$

$$\mu_{CCW} = \frac{\mu_{max,CCW} \times C_{CCW}}{k_{S,CCW} + C_{CCW}} \quad (2)$$

Where, μ = Specific growth rate of *Shewanella putrefaciens* MTCC 8104; μ_{max} = Maximum Specific growth rate of *Shewanella putrefaciens* MTCC 8104; k_S = Saturation constant; Subscripts Lac stand for lactic acid and Cottage cheese whey (CCW) respectively.

Model Formulation

The mathematical models for the prediction of performance of two sets of batch MFCs, namely, MFC-Lac and MFC-CCW are based on the following assumptions:

- The cells are completely in suspended form in all the MFCs
- The pH and temperature are constant
- The electrical resistances of electrodes and the ion exchange membrane are negligible
- As in case of *Shewanella oneidensis,* the microbial culture of *Shewanella putrefaciens* MTCC 8104, does not need any mediator for the electron transport. The electrons can be transported directly from suspended cells to the anode surface[20].

Anode chamber

Half Cell reactions

The chemical reaction occurring in the anode chamber of MFC-Lac and MFC-CCW are as follows:
Lactic acid
$$C_3H_6O_3 + 2H_2O \rightarrow CO_2 + 4H^+ + 4e^- \quad (3)$$

The reaction of lactic acid is based on the pathway of its assimilation by *Shewanella sp.* Under anaerobic condition, lactic acid is converted to acetic acid with the liberation of four protons and electrons each [Luo et al., 2019]. Acetic acid cannot be assimilated by *Shewanella sp* under anaerobic condition [Zhang et al.,2021].

Mole balance equations

Biomass

The rate of change of biomass concentration due to growth in the anode chamber in case of MFC-Lac and MFC-CCW
$$\frac{dC_X}{dt} = \mu_i C_x \quad (4)$$

Where, $\mu_i$is the specific growth rate of the bacteria on substrate, S_i, C_x is the biomass concentration. For MFC-Lac, $\mu_i = \mu_{Lac}$ and for MFC-CCW, $\mu_i = \mu_{CCW}$.

Substrates

For MFC-Lac and MFC-CCW oxidation of lactic acid occurs in the anode chamber. In general, the consumption of substrate,S_i in the anode chamber can be represented by Nernst Monod model as follows:
$$\frac{dC_{S_i}}{dt} = -\frac{1}{Y_{\left(\frac{x}{S_i}\right)}} * \mu_i * \left(\frac{1}{1+exp\left(-\frac{F}{RT}\eta\right)}\right) * C_x \quad (5)$$

In equation 5, 'F' is the Faraday's constant, 'R' is the universal gas constant, 'T' is the operating temperature and 'η' is the anode activation over-potential, i.e., the extra voltage required to overcome the energy barrier for electron transfer from electroactive bacteria to the anode. Thus, the consumption rates of lactic acid and lactic acid in CCW in the anode chamber are as follows:
$$\frac{dC_{Lac}}{dt} = \left(-\frac{1}{Y_{\left(\frac{x}{Lac}\right)}}\right) \times \mu_{\text{Lac}} \times \left(\frac{1}{1+exp\left(-\frac{F}{RT}\eta\right)}\right) \times C_x \quad (6)$$
$$\frac{dC_{CCW}}{dt} = \left(-\frac{1}{Y_{\left(\frac{x}{CCW}\right)}}\right) \times \mu_{CCW} \times \left(\frac{1}{1+exp\left(-\frac{F}{RT}\eta\right)}\right) \times C_x \quad (7)$$

CO_2

According to equations 3, the rate of generation of 'CO_2' in the anode chamber is as follows:

MFC-Lac:

$$\frac{dC_{CO_2}}{dt} = -(\frac{dC_{Lac}}{dt}) \quad (8)$$

MFC-CCW:

$$\frac{dC_{CO_2}}{dt} = -(\frac{dC_{CCW}}{dt}) \quad (9)$$

H^+ and e^-

According to equations 3, the rate of generation of proton and the electron in the anode chamber is as follows:

MFC-Lac:

$$\frac{dC_{H^+}}{dt} = \frac{dC_{e^-}}{dt} - (4 \times \frac{dC_{Lac}}{dt}) \quad (10)$$

MFC-CCW:

$$\frac{dC_{H^+}}{dt} = \frac{dC_{e^-}}{dt} - (4 \times \frac{dC_{CCW}}{dt}) \quad (11)$$

Cathode chamber

Half Cell reactions

The reaction in thecathode chamber for both MFC-Lac, and MFC-CCW is as follows:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (12)$$

Mole Balance Equations

Oxygen is transferred externally and is consumed through the reaction with protons and electrons at the cathode. Therefore, mass transfer and reactions occur simultaneously. According to Equation 14, one mole of oxygen reacts with four moles of protons, transferred from the anode to the cathode chamber through the PEM.

$$\frac{dC_{O_2}}{dt} = k_L a_{O_2} * \left(C^*_{O_2} - C_{O_{2L}}\right) - f * \frac{1}{4} * \frac{V_a}{V_c} * \frac{dC_{H^+}}{dt} \quad (13)$$

Here, $k_L a_{O_2}$' is the overall volumetric oxygen mass transfer coefficient; '$C_{O_{2L}}$'is the dissolved oxygen concentration in the cathode fluid, '$C^*_{O_2}$' is the equilibrium or saturation concentration at the gas-liquid interface.'V_a' and 'V_c' are working volumes of the anode and the cathode chambers. 'f' stands for the fraction of electrons transferred to the anode and has been used as an adjustable parameter in the model.

The differential mole balance equations 6-11 and 13 have been solved with the aid of ode45 of MATLAB using the following initial conditions.

At $t = 0$,

$$\begin{bmatrix} C_X = C_{X0} \\ C_{Lac} = C_{Lac0} \\ C_{CCW} = C_{CCW0} \\ C_{CO_2} = 0 \\ C_{H^+} = 0 \\ C_{O_2} = C_{O_20} \end{bmatrix} \quad (14)$$

All model parameters have been provided in Table 1.

Electrochemical model

Electro-active bacteria (EAB) can transfer electrons by oxidizing substrates to a solid electrode. In this work, the Nernst equation is used for describing the electrochemical behaviour of the system and the equation is:

$$E_{cell} = E^0_{cell} - \frac{R*T}{n*F} ln(Q) \tag{15}$$

Where, Q is the reaction quotient, defined as follows:

$$Q = \frac{product\ of\ activity\ coefficients\ (or\ concentration\ )\ of\ products}{product\ of\ activity\ coefficients\ (or\ concentration\ )\ of\ reactants} \tag{16}$$

n = number of moles of electrons transferred due to the reactions in the anode and cathode chamber.

For anode half-cell reaction the equation followed by Nernst equation can be written as:

$$E_{anode} = E^0_{anode} - \frac{R*T}{n*F} ln(Q_{anode}) \tag{17}$$

For lactic acid consumption in both MFCs, $Q_{anode}$is represented by $Q_L$as follows:

$$Q_L = \left(\frac{[C_{CO_2}]*[C_{H^+}]^4}{[C_{C_3H_6O_3}]}\right) \tag{18}$$

Putting the value of Q_L in Equation 17 the E_{anode}using lactic acid,

$$E_{anode,L} = E^0_{anode,L} - \frac{R*T}{8*F} * Q_L \tag{19}$$

In the same manner, the potential of the cathode chamber can be calculated as:

$$E_{cathode} = E^0_{cathode} - \frac{R*T}{4*F} ln(Q_{cathode}) \tag{20}$$

Where, the value of $Q_{cathode}$can be calculated as follows:

$$Q_{Cathode} = \left(\frac{C_{H_2O}}{C_{O_2} \times C^4_{H+}}\right) \tag{21}$$

Substitution of $Q_{Cathode}$in equation 20 using equation 21 leads to,

$$E_{cathode} = E^0_{cathode} - \frac{R*T}{4*F} ln\left(\frac{C_{H_2O}}{C_{O_2} \times C^4_{H+}}\right) \tag{22}$$

The actual potential of the MFC usually differs from the theoretical value due to some losses, namely, activation loss, $\eta_{act}$and Ohmic loss, η_{ohm} [Esfandyari et al., 2017]. In general, the actual potential of an MFC can be calculated as follows:

$$E_{MFC} = \left(E_{cathode} - E_{anode,L}\right) - \eta_{act} - \eta_{ohm} \tag{23}$$

The equation of activation overpotential is as follows [Xing et al., 2009]:

MFC-Lac:

$$\eta_{act,MFC-lac} = \frac{b}{2.303} * sinh^{-1}\left(\frac{I_{cell}}{2*I_0*C_{Lac}}\right) \tag{24}$$

MFC-CCW:

$$\eta_{act,MFC-CCW} = \frac{b}{2.303} * sinh^{-1}\left(\frac{I_{cell,G}}{2*I_0*C_{CCW}}\right) \tag{25}$$

Where, I_{cell} = current generated due to the liberation of electrons through consumption of the substrate and the equation is:

$$I_{cell} = \frac{1}{3600} * f * F * V_a * \frac{dC_{e^-}}{dt} \tag{26}$$

The factor 3600 in Equation (29) is for unit conversion (1h=3600s).

The ohmic overpotential is calculated as follows [Rabaey et al., 2003]:

$$\eta_{ohm} = \left(\frac{d_m}{k_m} + \frac{d_{cell}}{k_{aq}}\right) * I_{cell} \quad (27)$$

Where, d_m and d_{cell} are the thickness of the membrane and the distance between the anode and the cathode respectively, and k_m and k_{aq} are respectively the conductivities of the membrane and the aqueous anolyte solution.

The current and power density, I_d and P_d , on the basis of the anode surface area, can be calculated as follows:

$$I_d = \frac{I_{cell}}{A} \quad (28)$$

$$P_d = \frac{I_{cell} \times E_{MFC}}{A} \quad (29)$$

Experimental model Validation:

To evaluate the accuracy of the developed mathematical model, statistical error analysis was carried out using Root Mean Square Error (RMSE) and Normalized Root Mean Square Error (NRMSE) between the experimental and simulated data. The RMSE quantifies the average deviation between model predictions and experimental observations, while NRMSE provides a dimensionless measure of error normalized with respect to the observed mean, allowing for better comparison across variables.

$$\text{RMSE} = \sqrt{\frac{1}{n} * \sum_{i=1}^{n} (y_i^{exp} - y_i^{sim})^2} \quad (30)$$

$$\text{NRMSE} = \frac{RMSE}{\bar{y}^{exp}} * 100 \quad (31)$$

Where, y_i^{exp}= experimental value at data point; y_i^{sim} = simulated (model-predicted) value at data point; n = total number of data points; $\bar{y}^{exp}$ = the mean of the experimental data.

Table 1: Model Parameters

Parameters	Description	Value
μ	Specific growth rate (h^{-1})	-
μ_L	Specific growth rate on lactic acid (h^{-1})	-
μ_{CCW}	Specific growth rate on glucose (h^{-1})	-
μ_{max}	Maximum specific growth rate (h^{-1})	0.11
$\mu_{max,CCW}$	Maximum specific growth rate of *Shewanella putrefaciens* in Glucose (h^{-1})	0.048
$\mu_{max,L}$	Maximum specific growth rate of *Shewanella putrefaciens* in lactic acid (h^{-1})	0.0314
k_s	Substrate saturation constant (mol/L)	-
$k_{s,G}$	Substrate saturation constant of *S.Putrefaciens* in CCW substrate(mol/L)	177.03
$k_{s,L}$	Substrate saturation constant of *S.Putrefaciens* in Lactic acid substrate(mol/L)	160.9
C_X	Concentration of bacteria (gm/L)	-
C_{X0}	Initial concentration of bacteria (gm/L)	0.05
C_{G0}	Concentration of Glucose (mol/L)	0.0056
C_{LO}	Concentration of Lactic acid(mol/L)	0.0336
$C_{CO_2,0}$	Concentration of initial CO_2 (mol/L)	0
$C_{H^+,0}$	Concentration of initial H^+ (mol/L)	0
$C_{e^-,0}$	Concentration of initial e^- (mol/L)	0

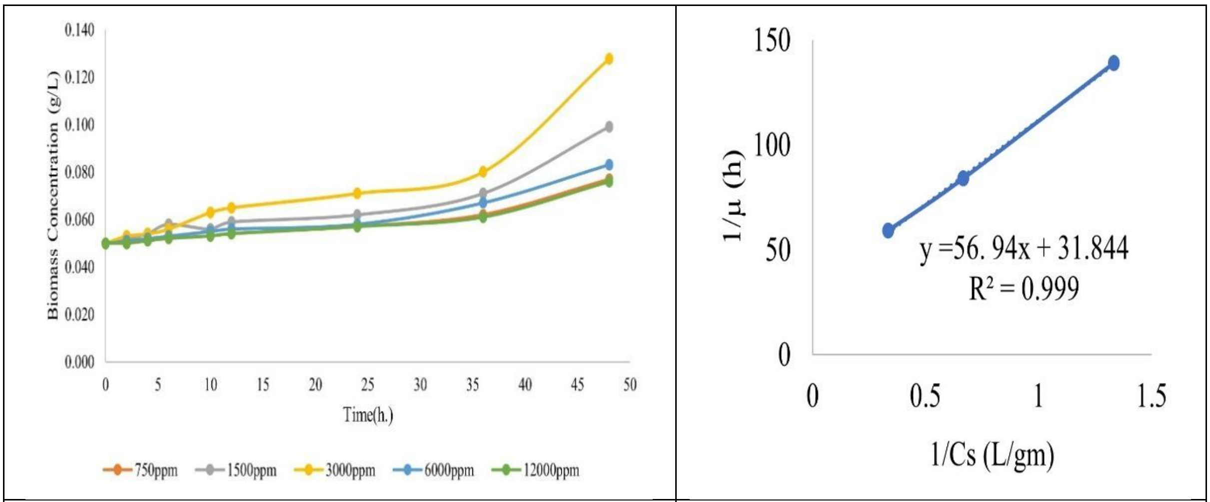
Parameters	Description	Value
$C_{O_2,0}$	Concentration of initial O_2 (mol/L)	0.000
$Y_{\left(\frac{x}{CCW}\right)}$	Yield coefficient in CCW (gm bacteria/gm glucose)	0.526
$Y_{\left(\frac{x}{L}\right)}$	Yield coefficient in Lactic acid (gm bacteria/gm Lactic acid)	0.572
R	Universal gas constant	8.314
T	Number of faradays	298
F	Temperature (K)	96500
$E^0_{anode,CCW}$	Standard anode potential of MFC-CCW (V)	0.34
$E^0_{anode,L}$	Standard anode potential of MFC-Lac (V)	0.34
$E^0_{cathode}$	Standard cathode potential of MFC(V)	0.81
b	Tafel coefficient(V)	0.05
I_0	Initial current (μA)	1
V_a	Volume of anode chamber(L)	0.1
V_c	Volume of cathode chamber(L)	0.25
d_m	Thickness of proton exchange membrane(m)	0.005
k_m	Conductivity of membrane (mS/m)	0.018
d_{cell}	Distance between the anode and cathode(m)	2.5e-2
k_{aq}	Conductivity of anolyte (mS/m)	3500 [Esfandyari et al.,2017]
A	Area of electrode(m^2)	0.0004

Result and Discussion

Kinetic Parameters of Growth on Lactic acid and CCW:

Shewanella putrefaciens MTCC 8104 growth on lactic acid:

The growth kinetics of *Shewanella putrefaciens MTCC 8104* were evaluated using lactic acid as the sole substrate at concentrations ranging from 750 ppm to 12,000 ppm, with both optical density and biomass concentration measured over time to monitor growth. The biomass growth curve is plotted in figure 2.(a). The growth curves exhibited a typical sigmoidal pattern, but no lag phase was observed as the culture was pre-adapted for 24 hours in lactic acid prior to inoculation, and the exponential phase was sustained up to 48 hours. Among the tested concentrations, maximum growth was achieved at 3000 ppm (3 g/L), beyond which growth declined, indicating a substrate inhibition effect at higher lactic acid levels. Kinetic analysis using Monod modeling and inhibition models revealed a maximum specific growth rate (μ_{max}) of 0.0314 h^{-1} and a substrate saturation constant (K_s) of 1.788 g/L, with a critical substrate concentration of 3000 ppm and an inhibition constant (K_i) of 5.034 g/L. These values were obtained from the slopes and intercepts of 1/μ vs 1/Cs plots in figure 2.(b). Additionally, the biomass yield coefficient ($Y_{X/S}$) was determined to be 0.572 g biomass per g lactic acid consumed, indicating the efficiency of carbon conversion from substrate to biomass under the tested conditions.

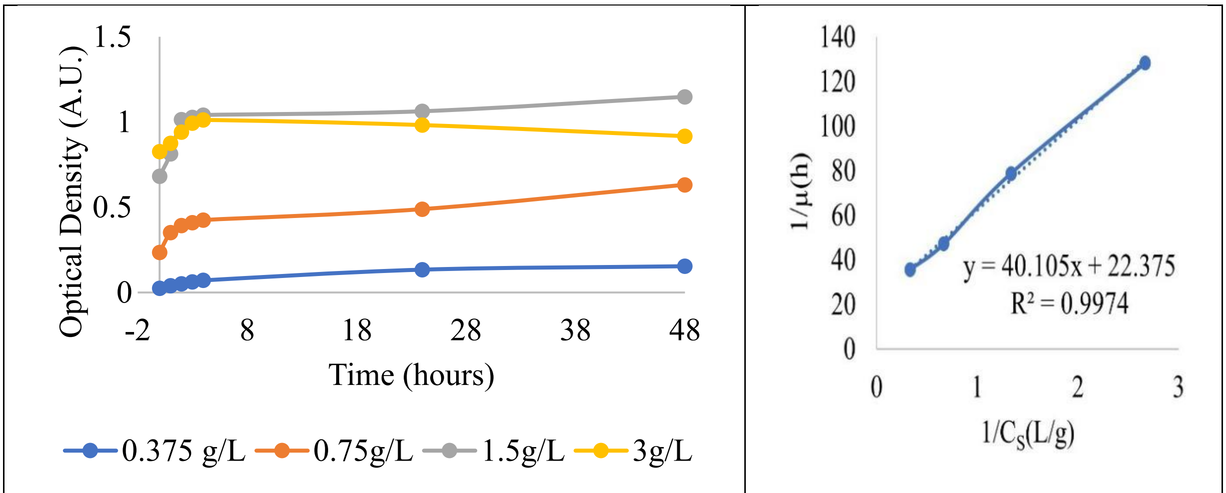


(a)	(b)

Figure 2: growth kinetics on pure lactic acid of *S.putrefaciens* (a)Biomass concentration (g/L) versus time(h.) plot; (b) 1/μ (h) vs 1/Cs (L/g) plot.

***Shewanella putrefaciens MTCC 8104* growth on CCW:**

The growth kinetics of *Shewanella putrefaciens MTCC 8104* on whey, a complex dairy effluent, demonstrate a strong substrate concentration dependence, as evidenced by the optical density data which shows significantly enhanced growth at higher concentrations, with the 1.5 g/L and 3 g/L cultures reaching ODs of 1.148 and 0.917 after 48 hours, compared to only 0.154 and 0.632 at the lower 0.375 g/L and 0.75 g/L concentrations, respectively potted in figure 3.(a) . Kinetic modelling via a Monod model plot of the inverse specific growth rates (1/μ) against inverse substrate concentrations ($1/C_S$) plotted in figure 3.(b)yielded a maximum specific growth rate (μ_{max}) of 0.048 h^{-1} and a notably high saturation constant (k_S) of 1.967 g/L, indicating that while the organism possesses a moderate capacity for rapid growth, it exhibits a low affinity for the whey substrate, requiring a high concentration to achieve half of its maximum growth rate. Consequently, the calculated biomass yield coefficient ($Y_{X/S}$) of 0.526 g biomass/g substrate, while reasonable, must be contextualized by these kinetics, suggesting that efficient biomass production and, by extension, effective electron generation for microbial fuel cell applications would necessitate operation at high, sustained whey concentrations to overcome the low substrate affinity and maximize metabolic activity.

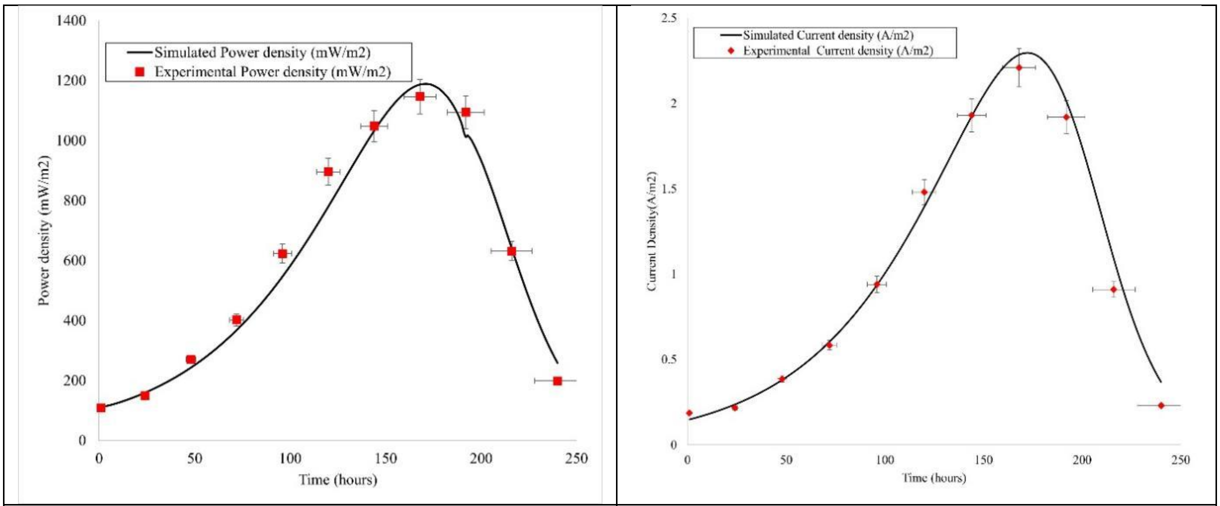


(a)	(b)

Figure 3: growth kinetics on cottege cheese whey of *S.putrefaciens* **(a)** Biomass concentration (g/L) versus time (h); **(b)** 1/μ (h) vs 1/Cs (L/g) plot.

Performance of MFC-Lac:

A double chambered MFC is developed using suspended culture of *Shewanella putrefaciensMTCC8104* in anode chamber is assessed by the electrical performance of the MFC with lactic acid as substrate having concentration of 3g/L. A total time period of 10 days the setup been observed for proper understanding of the performance. In Figure 4. (a) and (b), the experimental values of lactic acid power density and current density of MFC-Lac have been plotted against time. The corresponding simulated time-trajectories of the same variables, using mathematical model of MFC-Lac with initial lactic acid concentration of 3g/L, have been superimposed on the same figure. From the result it is observed that the highest produced power density is 1147 mW/m^2 and current density of 2.21 A/m^2 at the 168th hours of operation. The simulated time trajectories of current and power density match with experimental ones of MFC-Lac when the factor, f (Eq. 13) indicating the fraction of liberated moles of electrons reaching the anode, is set at 0.32. Thus, it is apparent that 32% of the total number of electron moles liberated due to substrate consumption is reaching the anode and in turn transported through the external circuit.



(a)	(b)

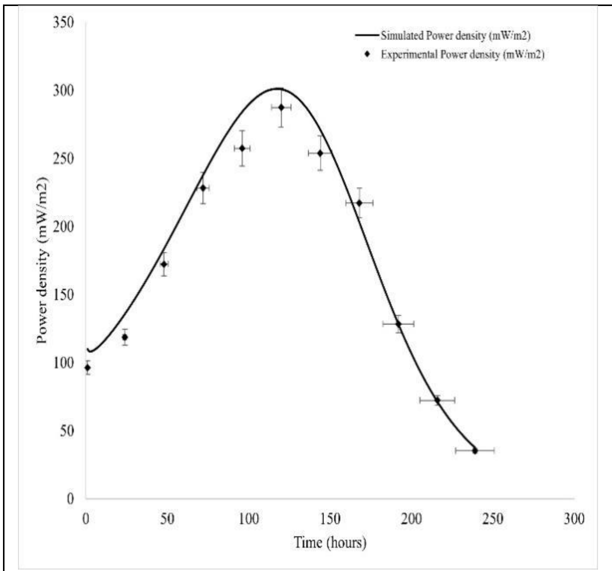
Figure 4: (a) Power density (mW/m^2); **(b)** Current density (A/m^2) versus time (hours) plot of MFC-Lac

When compared to other dual-chamber systems, MFC-Lac outperformed the *Desulfomicrobium baculatum*–based MFC, which produced 0.45 A/m² and 349 mW/m² at 6 g/L substrate concentration [Bratkova et al., 2019]. Similarly, it exceeded the performance of Shewanella-based systems using carbon felt electrodes, which reported only 0.007 A/m² and 0.227 mW/m² at 7.5 g/L substrate [Esfandyari et al., 2017]. The obtained current density was also comparable to that reported for single-chamber anaerobic sludge MFCs (2.18 A/m², 501.85 mW/m²) [Zhao et al., 2017], despite using a different inoculum and membrane configuration. Although the MFC-Lac did not reach the extremely high outputs reported in air-cathode sludge-based systems (35.2 A/m² and 7242.4 mW/m²) [Gao et al., 2017] or in dual-chamber setups using *Desulfuromonas acetoxidans* (9.1 A/m² and 5461.5 mW/m²) [Vasyliv et al., 2013], it should be noted that these systems used optimized electrode architectures, higher substrate loadings, or sludge consortia that promote broader metabolic diversity.

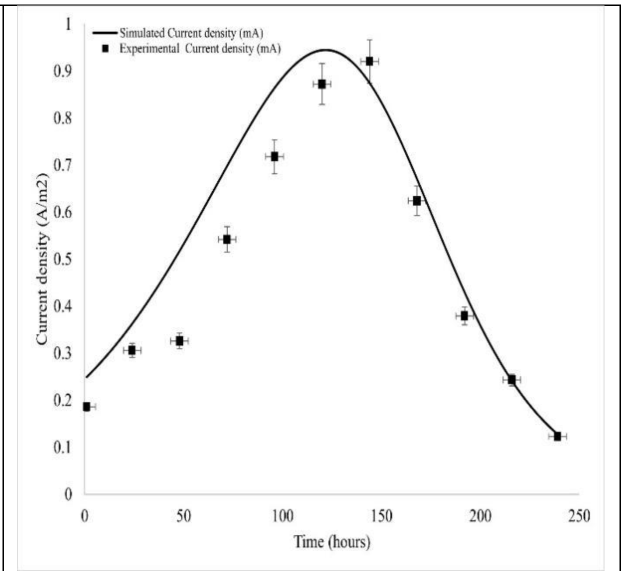
Performance of MFC-CCW:

A double-chambered MFCwas constructed with an anode chamber containing a suspended culture of *Shewanella putrefaciens MTCC 8104* and fed with cottage cheese whey, in which the lactic acid concentration was adjusted to 3 g/L as the primary substrate. The system was operated for 10 days to evaluate its bio-electrochemical performance. The MFC achieved a peak voltage of 486mV within 24 hours of operation, maintaining this steady state for three days before a gradual decline was observed in the subsequent days. In contrast, the current output reached its maximum value of 0.368 mA at the 144th hours of operation mark. This performance corresponded to a maximum power density of 287.48 mW/m² and a current density of 0.92 A/m², both also achieved at the 144-hour interval. Similar trends are seen elsewhere: Mahato et al. (2022) achieved just 0.0358 A/m² and 7.18 mW/m² with whey wastewater, while Gadima et al. (2025) reported modest improvements with yeast supplementation (3.4–4.4 A/m², 19–32 mW/m²).

Segundo et al. (2025), however, demonstrated unusually high outputs from raw whey in a Nafion-based MFC, reporting ≈44 A/m² and 15,850 mW/m², though these values likely reflect unit inconsistencies. The experimental values of MFC-CCW's power density and current density have been plotted against time in figure 5. The corresponding simulated time-trajectories of the same variables, using mathematical model of MFC-CCW with initial lactic acid concentration of 3g/L, have been superimposed on the same figure. From the analysis of the figure 5.(a) and 5.(b), it appears that although the performance pattern of MFC-CCW is similar to that of MFC-Lac, the current and power densities could reach only 41.63% and 25.1%%. This can be due to the interference of other compounds like lactose, peptides, proteins, fats etc present in whey. In this case, the simulated data and the experimental data are matched when the f factor (Eq. 13) valued 0.162 which means in MFC-CCW only 16.2% of total electron moles transferred through anode to cathode. This signifies that the MFC-CCW performance is 42.14 % with respect to MFC-Lac.



(a)



(b)

Figure 5. (a) Power density (mW/m2); **(b)** Current density (A/m2) versus time (hours) plot of MFC-CCW

Model Validation:

The microbial fuel cell (MFC) systems operated with pure lactic acid (MFC-Lac) and cottage cheese whey (MFC-CCW) were validated against the developed mathematical model. The predicted current density and power density were compared with experimental values using root mean square error (RMSE) and normalized RMSE (NRMSE). The results (Table X) indicate that the model successfully captures the experimental dynamics of both systems. For MFC-Lac, the RMSE for current density was 55.27, corresponding to an NRMSE of 7.82%, while the power density showed an NRMSE of 9.25%. For MFC-CCW, the RMSE values were 0.042 for current density and 13.38 for power density, with NRMSE values of 7.81% and 7.76%, respectively. These relatively low NRMSE values (<10%) confirm that the mathematical model is reliable for predicting both current and power density trends under different substrates. Moreover, the use of whey not only validates the model's accuracy but also highlights its practical significance in utilizing agro-industrial waste streams, thereby contributing to both environmental sustainability and economic feasibility in future large-scale MFC applications.

Table 2: RMSE and NRMSE table

System	RMSE		NRMSE	
	Current density	**Power density**	**Current density**	**Power density**
MFC-Lac	0.083	55.27	7.52%	9.25%
MFC-CCW	0.0t2	13.38	7.81%	7.76%

The mathematical model model is not fundamentally new in its *components* (NM, Monod kinetics), but is novel in its integration and successful, robust validation for the two distinct systems: 1) Unique Substrate Validation: Demonstrating that the same model accurately predicts the behavior of a pure, simple carbon source (lactic acid) and a complex industrial waste (cottage cheese whey) with excellent accuracy (NRMSE<10%). 2) Explicit Coupling: The successful integration of substrate kinetics and electrochemical losses, particularly how it captures the performance drop attributed to the complexity of the whey (MFC-CCW) substrate, highlights its ability to predict real-world complexity better than simpler models. This model is a dynamic bio-electrochemical model that successfully couples microbial kinetics with electrochemical principles. It belongs to a class of models frequently used in MFC research, but contains a key distinction which is tabulated in table 2.

Table 2: Comparison of the Mathematical Model with Existing Models reported in literature

Feature	Author's Model (MFC-Lac and MFC-CCW)	Established MFC Models (Literature)	Novelty/Significance of Authors' Approach
Kinetic Basis (Pinto et al.,2010; Esfandyari et al.,2017)	Monod Kinetics is used to describe microbial growth and substrate consumption rate (μ and C_S).	Monod Kinetics (or variations like Blackman/Tessier) is the *standard* approach for quantifying microbial growth in most dynamic MFC models	Standard, validated approach. The novelty lies in the *determined parameters* for *S. putrefaciens* on lactic acid and whey, which are unique to this study.
Electrochemical Coupling (e.g., Torres et al.,2007).	Uses the Nernst-Monod (NM) equation to link the anode potential to the substrate consumption rate and current generation.	NM is a widely recognized and validated model for anode-respiring bacteria (ARB) that use a *conductive biofilm* mechanism (e.g., *Geobacter*, *Shewanella*), describing the relationship between current density and anode potential losses	Confirmation of applicability. Successfully confirms the applicability of the Nernst-Monod framework for *S. putrefaciens* MTCC 8104 on two different, highly relevant substrates (pure lactic acid and complex dairy waste).
Electron Transfer Mechanism (Picioreanu et al., 2010); (Marcus et al., 2007).	Mediator-less system using *Shewanella putrefaciens* MTCC 8104, which typically relies on Extracellular Electron Transfer (EET) via cytochromes/biofilm conduction.	Models can be classified as: 1. Mediator-based (using soluble electron shuttles) (Picioreanu et al., 2010) or 2. Mediator-less (using EET/conduction). NM and Butler-Volmer-Monod (BVM) are common for mediator-less systems (Marcus et al., 2007).	Focus on EET. The model's success confirms the dominance of direct/conductive electron transfer in this specific *Shewanella* strain and setup, distinguishing it from older mediator-based models.
Activation Overpotential (ηact) Modeling (Picioreanu et al., 2010, BVM models)	The activation overpotential term is explicitly correlated with the substrate concentration via the Nernst-Monod component, resulting in a single model framework.	Most established models use the standard Butler-Volmer equation to model ηact, which depends on current density, exchange current density, and charge transfer coefficient, but does not typically include direct substrate concentration dependency within the activation term itself.	Key Novelty. The model's strength is its ability to use a single, unified mathematical structure to accurately predict performance for two vastly different feedstocks (pure/simple vs. complex/waste). The low NRMSE<10% validation for both scenarios (MFC-Lac and MFC-CCW) demonstrates a high degree of model robustness and generality—a frequent challenge in MFC modeling.

Conclusion: This study presents a comprehensive investigation into the performance and modeling of microbial fuel cells (MFCs) utilizing *Shewanella putrefaciens* MTCC 8104, with a focused comparison between pure lactic acid and lactic acid derived from cottage cheese whey (CCW) as substrates. The core achievement is the development and experimental validation of a robust mathematical model that integrates microbial growth kinetics, substrate degradation, and electrochemical electron transfer mechanisms. The model demonstrates exceptional predictive accuracy, with normalized root mean square error (NRMSE) values below 10% for both current and power density across both substrate types.

The experimental results established clear performance benchmarks, revealing crucial insights into substrate efficiency. The MFC fueled with pure lactic acid (MFC-Lac) achieved superior performance with a maximum power density of 1147 mW/m² and current density of 2.21 A/m², accompanied by an electron recovery efficiency of 32%. In contrast, the MFC operated on cottage cheese whey (MFC-CCW) attained substantially lower maximum values of 287.48 mW/m² and 0.92 A/m², representing performance reductions of approximately 75% and 58% respectively, with an electron recovery efficiency of only 16.2%. This quantitative comparison provides critical understanding: while the complex composition of whey—containing proteins, fats, and lactose—significantly impedes electron transfer efficiency and overall power generation, it remains a functionally viable substrate for bioelectricity production.

For scaled-up applications, the result of the research demonstrates practical implications. The successful utilization of cottage cheese whey, an abundant and low-cost agro-industrial byproduct, represents a significant advancement toward economically viable MFC systems. The model's robustness in handling both defined and complex waste streams makes it an invaluable engineering tool for scaling calculations and optimization of larger systems. When considering scale-up, the technology shows particular promise for decentralized, on-site wastewater treatment in small-to-medium dairy facilities, where it can function as an "energy-generating wastewater pre-treatment unit." While the absolute power output from whey may be best suited for low-energy applications, its primary value at scale lies in significantly reducing the organic pollutant load of dairy effluent—transforming a disposal burden into a source of sustainable bioelectricity, simultaneously addressing waste management challenges.

The implications of this research extend beyond technical performance to broader environmental and economic benefits. This approach directly addresses two pressing global challenges: the need for sustainable energy sources and the management of high-strength organic wastewater. By transforming a pollutant into a resource, the study presents a compelling case for implementing MFC technology within a circular bioeconomy framework, offering dairy industries a pathway to reduce their environmental footprint while generating decentralized energy.

In summary, this work makes a multifaceted contribution to the field of bioelectrochemical systems. It delivers a validated predictive model suitable for scale-up calculations, provides a rigorous comparative analysis of pure and waste substrates, and demonstrates a practical strategy for integrating energy production with wastewater treatment. The findings robustly indicate that whey-based MFCs represent a technologically feasible and economically attractive alternative for sustainable bioenergy generation and waste management in agro-industrial settings, with particular relevance for decentralized applications where waste treatment is the primary objective and energy recovery is a valuable bonus.

References:

Ateş E, Sanin SL. Investigation of the electrical potential of whey using a river sediment microbial fuel cell. Bulletin of the Chemical Society of Ethiopia. 2024 Jul 12;38(5):1479-91.

Borshchevskaya LN, Gordeeva TL, Kalinina AN, Sineokii SP. Spectrophotometric determination of lactic acid. Journal of analytical chemistry. 2016 Aug;71:755-8.

Bratkova S, Alexieva Z, Angelov A, Nikolova K, Genova P, Ivanov R, Gerginova M, Peneva N, Beschkov V. Efficiency of microbial fuel cells based on the sulfate reduction by lactate and glucose. International Journal of Environmental Science and Technology. 2019 Oct 1;16:6145-56.

Casallas-Ojeda M, Cabeza I, Sanchez N, Caicedo-Concha DM, Astals S. Cheese whey and dairy manure anaerobic co-digestion at psychrophilic conditions: Technical and environmental evaluation. Environmental Research. 2024 Jun 15;251:118525.

Chandra S, Pandit S, Roy A, Rab SO, Roy AK, Saeed M, Kumar A, Sharma K, Ranjan N, Raj S. Bioenergy recovery from jackfruit waste via biohydrogen production through dark fermentation and power generation through stacked microbial fuel cells. International Journal of Hydrogen Energy. 2025 Feb 10;102:845-55.

Esfandyari M, Fanaei MA, Gheshlaghi R, Mahdavi MA. Mathematical modeling of two-chamber batch microbial fuel cell with pure culture of Shewanella. Chemical Engineering Research and Design. 2017 Jan 1;117:34-42.

Feng F, Wu CH, Li F, Wang X, Zhu J, Zhang R, Chen SC. Research on the integration of microbial fuel cells with conventional wastewater treatment technology: Advantages of anaerobic fermentation. Energy Conversion and Management: X. 2024 Aug 5:100680.

Gadima SB, Ukanwa SO, Olaifa JT. Treatment of Cheese Whey and Bioelectricity Generation in MFCs as a Substitute Source of Energy in Wastewater. Journal of Bioresources and Environmental Sciences. 2025 Apr 1;4(1):55-70.

Gao C, Wang A, Wu WM, Yin Y, Zhao YG. Enrichment of anodic biofilm inoculated with anaerobic or aerobic sludge in single chambered air-cathode microbial fuel cells. Bioresource technology. 2014 Sep 1;167:124-32.

Ghaly AE, Kamal M, Correia LR. Kinetic modelling of continuous submerged fermentation of cheese whey for single cell protein production. Bioresource technology. 2005 Jul 1;96(10):1143-52.

Kanellos G, Zonfa T, Polettini A, Pomi R, Rossi A, Tremouli A, Lyberatos G. A dual-chamber Microbial Electrolysis Cell for electromethanosynthesis from the effluent of cheese whey dark fermentation. Biomass and Bioenergy. 2024 Oct 1;189:107335.

Kato Marcus A, Torres CI, Rittmann BE. Conduction-based modeling of the biofilm anode of a microbial fuel cell. Biotechnology and bioengineering. 2007 Dec 15;98(6):1171-82.

Kim HJ, Park HS, Hyun MS, Chang IS, Kim M, Kim BH. A mediator-less microbial fuel cell using a metal reducing bacterium, Shewanella putrefaciens. Enzyme and Microbial technology. 2002 Feb 14;30(2):145-52.

Luo S, Guo W, H. Nealson K, Feng X, He Z. 13C pathway analysis for the role of formate in electricity generation by Shewanella oneidensis MR-1 using lactate in microbial fuel cells. Scientific reports. 2016 Feb 12;6(1):20941.

Mahato J, Miah M, Shovon MS, Roy N, Easmin MS, Sharma SC. Electricity production by microbial fuel cell using cheese whey wastewater of the dairy industry in Rajshahi, Bangladesh. Chemical and Biochemical Engineering Quarterly. 2021;35(4):421-30.

Ojha R, Pradhan D. The potential of microbial fuel cell for converting waste to energy: An overview. Sustainable Chemistry for the Environment. 2024 Dec 25:100196.

Picioreanu C, Head IM, Katuri KP, van Loosdrecht MC, Scott K. A computational model for biofilm-based microbial fuel cells. Water research. 2007 Jul 1;41(13):2921-40.

Picioreanu C, Katuri KP, Van Loosdrecht MC, Head IM, Scott K. Modelling microbial fuel cells with suspended cells and added electron transfer mediator. Journal of applied electrochemistry. 2010 Jan;40(1):151-62.

Pinto RP, Tartakovsky B, Perrier M, Srinivasan B. Performance analyses of microbial fuel cells operated in series. IFAC Proceedings Volumes. 2010 Jan 1;43(5):547-52.

Rabaey K, Lissens G, Siciliano SD, Verstraete W. A microbial fuel cell capable of converting glucose to electricity at high rate and efficiency. Biotechnology letters. 2003 Sep;25:1531-5.

Rincón-Catalán NI, Pérez-Fabiel S, Mejía-González G, Herrera-López D, Castro-Chan R, Cruz-Salomón A, Sebastian PJ. Power generation from cheese whey treatment by anaerobic digestion and microbial fuel cell. Waste and Biomass Valorization. 2022 Jul;13(7):3221-31.

Segundo RF, Luis CC, Otiniano NM, De La Cruz-Noriega M, Gallozzo-Cardenas M. Utilization of Cheese Whey for Energy Generation in Microbial Fuel Cells: Performance Evaluation and Metagenomic Analysis. Fermentation. 2025 Mar 26;11(4):176.

Seyezhai, R. and Mathur, B.L., 2011. Mathematical modeling of proton exchange membrane fuel cell. *International Journal of Computer Applications*, *20*(5), pp.1-6.

Torres CI, Kato Marcus A, Rittmann BE. Kinetics of consumption of fermentation products by anode-respiring bacteria. Applied microbiology and biotechnology. 2007 Dec;77(3):689-97.

Vasyliv OM, Bilyy OI, Ferensovych YP, Hnatush SO. Application of acetate, lactate, and fumarate as electron donors in microbial fuel cell. InReliability of Photovoltaic Cells, Modules, Components, and Systems VI 2013 Sep 24 (Vol. 8825, pp. 170-176). SPIE.

Watson VJ, Logan BE. Power production in MFCs inoculated with Shewanella oneidensis MR-1 or mixed cultures. Biotechnology and bioengineering. 2010 Feb 15;105(3):489-98.

Xing D, Cheng S, Regan JM, Logan BE. Change in microbial communities in acetate-and glucose-fed microbial fuel cells in the presence of light. Biosensors and Bioelectronics. 2009 Sep 15;25(1):105-11.

Zeng Y, Choo YF, Kim BH, Wu P. Modelling and simulation of two-chamber microbial fuel cell. Journal of Power Sources. 2010 Jan 1;195(1):79-89.

Zhang J, Chen Z, Liu C, Li J, An X, Wu D, Sun X, Zhang B, Fu L, Li F, Song H. Construction of an acetate metabolic pathway to enhance electron generation of engineered Shewanella oneidensis. Frontiers in Bioengineering and Biotechnology. 2021 Nov 19;9:757953.

Zhao YG, Zhang Y, She Z, Shi Y, Wang M, Gao M, Guo L. Effect of substrate conversion on performance of microbial fuel cells and anodic microbial communities. Environmental engineering science. 2017 Sep 1;34(9):666-74.

Scaling Up Non-Recyclable Plastic Waste (NRPW) Management in India: Policy and Technical Insights from Cement Kiln Co-Processing and Waste-to-Energy Incineration

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ABSTRACT

India generates ~26,000 tonnes of plastic waste daily, with a large non-recyclable fraction (NRPW) - notably films, multilayer laminates, and composites - that is difficult to manage due to heterogeneity and contamination. Mixed NRPW originates from RDF produced from municipal solid waste and legacy dumps; industrial streams (e.g., paper-recycling rejects, multilayer plastics from FMCG packaging under EPR, and composites); residues from sorting/recycling facilities; cleanup and remediation activities (river and beach cleanups, and upstream interception at barriers or dams); and persistent, hard-to-treat fractions (PFAS-containing materials, brominated flame retardants, complex composites). Cement-kiln co-processing and waste-to-energy (WtE) incineration are complementary end-of-life pathways that enable energy recovery, coal substitution, and landfill diversion within a circular economy. This paper evaluates technical, regulatory, and financial barriers - RDF variability, feedstock contamination, chlorine and ash management, pre-processing limits, and enforcement gaps - and finds that co-processing of dry, low-chlorine NRPW maximizes fossil-fuel displacement, while WtE provides city-scale throughput for mixed, wetter MSW. A 2025–2035 roadmap recommends a dual-track deployment - spec-grade RDF to kilns and mixed MSW to WtE - enabled by national RDF standards with quality-linked pricing, regional pre-processing hubs, progressive TSR targets (15–20%), CEMS-based emissions monitoring with public disclosure, outcome-based permitting, and integrated EPR tracking to scale compliant, financially viable NRPW management.

Keywords: Non-Recyclable Waste, Waste utilisation in Cement plant, Energy from Waste, Refuse-Derived Fuel (RDF), Extended Producer Responsibility.

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1. Introduction

1.1 Scale of India's Plastic Waste Challenge

India generates ~26,000 tonnes of plastic waste daily (~9.5 million tonnes annually) (Dhodapkar et al., 2023). India's annual plastic waste generation estimates vary widely, ranging from 4.1 to 27.8 million tonnes per annum (Cottom et al., 2024). CPCB estimates 50–55%

of plastic waste is non-recyclable, mainly from poor segregation contaminating recyclables. This hard-to-manage fraction demands urgent systemic action. India has over 3,000 recycling units with an installed capacity of 4.8 million tonnes per year (India Plastics Pact, 2022). While the plastic recycling rate is often reported at 50–60% (Kapur-Bakshi et al., 2021), the actual rate is much lower, as reported figures include collected or traded plastics, many of which never reach formal recycling pathways (India Plastics Pact, 2022). Of the 9.2 billion tonnes of plastic produced globally, only 9% has been recycled, while 79% has accumulated in landfills or natural environments (Geyer et al, 2017). The Ministry of Environment, Forest and Climate Change has been instrumental in formulating policies and regulations, including Extended Producer Responsibility (EPR) frameworks, that incentivize recyclers and integrate the informal sector into formal recycling systems. These initiatives aim to streamline waste management and promote eco-friendly production across industries.

Shri Yadav said that the government has laid down the policies but Industry-wide adoption of circular approaches is critical to driving sustainable growth and resource efficiency. The Minister highlighted 4 key strategies in this direction:

1. **Redesigning Products for Circularity:** Companies must move beyond single-use models and design products for recyclability. The integration of biodegradable, reusable, and modular components will help extend product life cycles and reduce waste.
2. **Investment in Advanced Recycling Technologies:** Adoption of emerging technologies can transform waste management systems, thereby improving recovery rates.
3. **Strengthening Supply Chain Collaboration:** Businesses need to collaborate across the value chain to optimize resource utilization, create closed-loop production systems, and build markets for secondary raw materials.
4. **Consumer Awareness and Behavioural Change:** Circularity requires active consumer participation. Industries must invest in campaigns to engage consumers, incentivize recycling, and promote sustainable consumption behaviours.

1.2 Major Sources and Nature of NRPW

Mixed non-recyclable plastic waste (NRPW) includes RDF from municipal solid waste and legacy dumps; industrial plastics such as rejects from paper recycling, multilayer plastics (MLPs) from FMCG packaging (often covered under EPR), and composites; residues from recycling facilities; cleanup and remediation waste including river and beach cleanups, as well as NRPW intercepted upstream of rivers in natural barriers or dams; and persistent, hard-to-treat fractions such as PFAS-containing materials, brominated flame retardants (BFRs), and complex composites.

1.3 Technical and Environmental Barriers

The heterogeneous and contaminated nature of NRPW makes mechanical recycling nearly impossible (CPCB, 2020). Calorific values vary widely - from 5,000-7,000 kcal/kg for clean films and MLPs to 1,500-2,000 kcal/kg for legacy RDF with soil and inerts - necessitating drying, sorting, and blending. These dynamics demand technically robust, economically viable, and environmentally compliant solutions.

1.4 Large Scale End-of-Life Solutions: Co-processing and WtE

The Ministry has notified a number of market-based Extended Producer Responsibility (EPR) Regulations, including those on e-waste, end-of-life vehicles, plastic packaging, waste tyres, waste batteries, used oil. The revenue earned by registered recyclers from sale of EPR certificates is additional profit earned over and above the profit generated from the sale of recycled product, he added.

Table 1 outlines the four end-of-life options recognized under India's EPR framework - cement-kiln co-processing, waste-to-energy (WtE), plastic-to-oil, and use of plastic in road construction. India's large-scale NRPW diversion rests on two core pathways: (1) cement-kiln co-processing, which uses NRPW as an alternative fuel and raw material (AFR), and (2) WtE incineration, which recovers electricity and heat from mixed waste.

Table 1: End of life disposal options for NRPW, as recognized in India's EPR Framework

End-of-Life Disposal Method	Description	Benefits
Cement Kiln Co-processing	Uses plastic waste as an alternative fuel or raw material in cement kilns.	High energy recovery and destruction efficiency, zero residue as ash is integrated into the cement product.
Waste-to-Energy (WTE)	Converts non-recyclable plastic waste into usable energy (electricity or heat) via incineration.	Reduces landfill dependency and recovers energy from waste.
Plastic-to-Oil (PTO)	Converts plastic waste into pyrolysis oil or fuels through advanced technologies.	Provides a disposal route for low-value plastics and produces alternative fuels but requires stringent emission controls and economic feasibility
Plastic in Road Construction	Mixes shredded plastic with bitumen for roadbuilding.	Improves road durability and provides a sustainable outlet for flexible plastics like single-use bags. Regulated by the Indian Roads Congress and other standards.

The number of cement plants using alternative fuels and raw materials (AFR) increased from 12 in 2010 (Saha et al., 2020) to over 80 today. Together, the industry now co-processes more than 2 million tonnes per year of mixed non-recyclable plastic waste (NRPW) and refuse-derived fuel (RDF). In comparison, Waste-to-Energy (WtE) plants with a combined capacity of 200 MW treat around 5 Mtpa of municipal solid waste (MSW), though actual utilisation is often lower due to poor waste quality and operational constraints. India has harnessed only 5.5% of its estimated 3,600 MW Waste-to-Energy potential.

Both are officially recognized under India's Extended Producer Responsibility (EPR) framework. MoEF&CC has established emission limit values (ELVs), including PCDD/F thresholds aligned with international BAT/BEP standards, and SOPs for fuel handling, monitoring, and feedstock quality.

1.5 Policy Context

The deadlock at INC 5.2 of the Global Plastics Treaty highlights a major policy gap: while negotiations focus on curbing future plastic production, more than five billion tonnes of legacy plastics already pollute the environment, steadily fragmenting into microplastics. This '*fragmentation gap'* (Kvale et al., 2024), calls for pragmatic, industry-driven solutions.

1.6 India's Legacy Waste Remediation Efforts

India is actively remediating dumpsites: of ~250 million tonnes of accumulated waste, ~60% has been recovered (MoHUA SBM Urban Dashboard), with over USD 1 billion allocated for projects. Cement co-processing and WtE incineration stand out as deployable end-of-life solutions for the legacy fraction.

1.7 Role of Industry and Partnerships

Cement companies can accelerate action by integrating NRPW into kiln operations with pre-processing and quality controls; documenting TSR, emissions, and destruction rates to support future treaty recognition; and engaging policymakers to align incentives with EPR and remediation. Partnerships with municipalities, recyclers, and aggregators will be critical to secure feedstock and scale circular value chains.

1.8 SINTEF Projects in India

2010–2015: CPCB–SINTEF Project built India's regulatory and technical foundation for co-processing—training CPCB, delivering five guidance documents and multiple emissions studies, and executing the ACC Kymore CFC destruction (16,300 kg; ≈131,000 tCO_2-eq)—while revealing early gaps in steel and power-sector co-firing.

2017–2024: SINTEF Phase II (cement industry) partnered with GIZ, NCCBM, CMA, CII, and RTI India to scale RDF/sludge co-processing through baselines, feasibility studies, plant trials, and bankable cost-recovery models—lifting national co-processing 10× from ~0.5% (2010) to >5% (2024) with several plants >30% TSR, and underpinning CPCB ELVs (2016), Co-processing Guidelines (2017), and GIZ/MoHUA RDF Guidelines (2019), enabling >80 plants under EPR and mobilizing tens of millions USD in private investment.

2019-2025: The OPTOCE project (https://optoce.no/), funded by Norad and led by SINTEF, has demonstrated the power of co-processing at scale. It piloted 20 large-scale demonstrations across 8 Asian countries (Bangladesh, Cambodia, China, India, Philippines, Sri Lanka, Thailand and Vietnam). These pilots diverted over 1 Mt of NRPW from rivers and dumpsites, substituted 0.5 Mt of coal, and achieved substantial CO_2 reductions. Scientific assessments confirmed that co-processing of NRPW is environmentally safe, with no elevated emissions of dioxins or other pollutants.

2. Methodology

The paper synthesizes technical, environmental, and economic evidence from SINTEF's Norwegian-funded programmes in India (2010–2024) and regional OPTOCE pilots (2019–2025). The paper centres on cement-kiln co-processing of NRPW, with selective WtE comparisons where they add value. Methods draw on plant-scale demonstrations and test burns in India, alongside policy-finance work (guideline development with CPCB/MoHUA, multi-stakeholder engagements, and cost-recovery modelling). Findings are triangulated across project reports, peer-reviewed literature, and operator datasets under formal permissions, providing a general, decision-oriented evidence base.

3. Cement Kiln Co-Processing: Sector-Specific Challenges

India has over 600 million tonnes (Mt) of annual cement production capacity and produced 426 Mt in 2023–24 (GCCA/TERI, 2025). The use of alternative fuels has grown steadily. In 2010, the TSR of UltraTech Cement and ACC was just 0.47% and 0.59%, respectively (Karstensen, K. H. and Saha, P. K., 2016). Today, large producers such as Dalmia Cement, JK Cement, JSW Cement, Adani Cement (ACC and Ambuja), UltraTech, and Shree Cement have adopted co-processing (Table 2). In 2024, their best plants achieved TSRs of 10–30%. However, these frontrunners cannot represent the entire sector, which maintains a national average TSR of only 5–6%, still far below the EU average of ~50%.

India has undertaken 90+ co-processing trials, largely with hazardous wastes. A landmark SINTEF/CPCB burn at ACC Kymore destroyed 16,300 kg of CFC-11/12/113 (≈131,000 t CO_2-eq.), surpassing Montreal Protocol/UNEP destruction-efficiency benchmarks (Karstensen et al., 2014). Scale-up remains constrained by feeding/handling bottlenecks, variable NRPW quality, and uneven kiln infrastructure. Although >80 cement plants are CPCB-authorized to co-process, only a subset currently operates at meaningful thermal substitution rates.

Table 2: Major cement companies co-processing mixed NRPW/RDF in India

SN	Cement Plant (Company)	Location (State)	TSR Achieved (2024)	Remarks
1	**Dalmia Cement**	Tamil Nadu, Odisha	~20%	Installed chlorine bypass; target: 100% TSR by 2035 and carbon-neutral by 2040.
2	**JK Cement**	Rajasthan, Karnataka	~16%	Target: 35% TSR by 2030.
3	**ACC Cement**	Karnataka, Madhya Pradesh	~11%	Early AFR adopter; target: 28% TSR by 2030.
4	**JSW Cement**	Andhra Pradesh	~10%	Nandyal plant co-processes RDF & MLP; target: 30% TSR by 2030.
5	**Ambuja Cement**	Gujarat, Rajasthan, Chhattisgarh	~8%	RDF among main alt fuels; targeting ~28% TSR by 2028.
6	**UltraTech Cement**	Pan-India (50+ plants)	~6%	Largest producer; supports 80 municipalities on waste; 20% raw material substitution rate; net-zero by 2050 goal
7	**Shree Cement**	Rajasthan, Chhattisgarh	~3%	TSR ~3% vs 15% FY24 target; ramping up AFR usage investments.
Sources: Company sustainability reports and annual reports (2024–2025); Personal communications.				

3.1 Fuel Quality & Pre-processing Constraints (Supply-side)

Cement kilns require spec-grade RDF/NRPW—stable calorific value, low moisture, and controlled chlorine/ash—but legacy dumpsites and mixed MSW often contain high moisture, fines, metals, and inerts that depress CV and raise ash (CPHEEO, 2018). Limited advanced pre-processing (drying, shredding, ferrous/non-ferrous removal, optical sorting, blending) constrains kiln-ready supply and caps achievable TSR and scale. With standardized RDF, kilns can lift TSR, directly displace coal, and advance decarbonization. Unlike other disposal routes, co-processing achieves complete thermal destruction (~2,000 °C gas; ~1,450 °C material temperature) and locks mineral residues into clinker, eliminating secondary ash disposal.

3.2 Clinker Integrity & Product Performance (Process-side)

High substitution rates depend on protecting clinker mineralogy and cement quality. Variability in particle size and ash chemistry (alkalis, S, Cl) can affect burnability, coating, and strength development (Ghosh et al, 2022). Operators must select the right feed points (avoid cold-end), manage alkali/Cl/S cycles (bypass where justified), and enforce tight QA/QC and lab checks to meet product specifications while raising TSR.

3.3 Chlorine Management

Excess chlorine in RDF can cause alkaline chloride build-up and cyclone clogging, kiln corrosion, refractory damage, and emission spikes (Caputo, A.C., & Pelagagge, P.M., 2002). Plants must continuously monitor chlorine content, use bypass systems where necessary, and manage feed points strategically. Failure to control chlorine can compromise clinker quality, reduce kiln life, and create regulatory non-compliance risks.

4. **Waste-to-Energy (WtE) Incineration: Sector-Specific Challenges**

Waste-to-Energy (WtE) Incineration plants handling municipal solid waste are classified under the Blue Category in CPCB's revised pollution index system, emphasizing their role as essential environmental services for domestic waste management (CPCB, 2025). India has about two dozen Waste-to-Energy (WtE) projects with a combined capacity of more than 200 MW and a designed throughput of 20,000–25,000 tonnes of raw MSW per day, though actual processing is lower due to poor feedstock quality and frequent downtime.

Table 3: Major waste-to-energy incineration plants in India

SN	City/Location	Operator / Agency	Capacity (MW)	Issues & Status
1	**Narela-Bawana, Delhi**	Re Sustainability Ltd (Ex Ramky Enviro)	24	Steady output, minimal downtime.
2	**Okhla, Delhi**	Jindal Urban (Timarpur-Okhla)	16	Frequent shutdowns; poor RDF fuel quality and emissions compliance issues.
3	**Ghazipur, Delhi**	EverEnviro Resource Management	12	Strong public opposition; repeated outages.
4	**Hyderabad (Telangana)**	Hyderabad Integrated MSW Ltd.	19.5	Receives largely unsegregated mixed waste, affecting efficiency.
5	**Bengaluru (Karnataka)**	KPCL / Private partner	12	Plant struggling with poorly segregated waste input.
6	**Jabalpur (Madhya Pradesh)**	Essel Infra (Jabalpur MSW Pvt.)	11.5	Small-scale steady run.
7	**Pune (Maharashtra)**	Decentralized operator	10	Low-calorific feedstock hindered output.
8	**Chandigarh**	SPML Infra	6	Intermittent operations; frequent breakdowns and long downtime periods.
Sources: ISWMAW (2023); CSE (2020).				

Most plants use mass-burn incineration, while few in Uttarakhand supply steam to paper mills via RDF boilers. Delhi operates four WtE plants - Okhla (21 MW), Narela-Bawana (24 MW), Ghazipur (12 MW), and Tehkhand (20 MW), processing ~9,800 tonnes/day, with more capacity planned. Table 3 profiles key waste-to-energy (WtE) plants across India.

While WtE plants can recover energy and reduce landfill use, waste heterogeneity, inadequate preprocessing, inconsistent RDF quality, and emission concerns limit scalability. Many plants also suffer from frequent downtime and financial non-viability (CSE, 2020; NITI Aayog, 2021; ISWMAW, 2023).

4.1 Combustion Control and Emissions

Mixed MSW heterogeneity drives incomplete combustion and CO-spikes, raising risk of dioxins/furans, HCl, SOx, NOx without advanced Air Pollution Control (APC) and tight operation control (Chyang et al., 2010; NITI Aayog, 2021). WtE plants must install Continuous Emission Monitoring System (CEMS) for real-time monitoring of PM, NOx, SO_2, CO, HCl, HF, CO_2, ensuring compliance with SWM Rules, 2016 (CPCB, 2025).

A 2020 CPCB study reported excessive dioxin and furan emissions at Delhi's WtE plants - Okhla (0.99 ng I-TEQ/Nm^3), Bawana (0.49), and Ghazipur (0.27) - far exceeding the limit of 0.1 ng I-TEQ/Nm^3 (CPCB, 2021). This underscores the urgent need for stricter emission standards, real-time monitoring, and advanced flue gas treatment systems to protect public health and ensure compliance.

Under the OPTOCE project, SINTEF ran a pilot in Feb 2024 at Jindal's Visakhapatnam WtE plant, processing 1,000-1,100 tonnes/day of MSW and 150-200 tonnes/day of RDF (containing 57.5% plastic). Three fuel mixes (100% MSW, 50/50, 25/75 MSW-RDF) met MOEFCC emission limits.

4.2 Clogging and Equipment Damage

Low-melting plastics, metals, and soil fractions cause feeder clogging, grate slagging, and abrasion of equipment (Lázár, I., et al., 2015; Wan, Y., et al., 2008). These operational challenges increase downtime and maintenance costs, reducing overall plant availability and operational efficiency. Regular maintenance schedules and robust equipment design are essential to sustain continuous operation.

4.3 Ash Management

WtE plants generate bottom ash (20–30%) and fly ash (2–3%) (CPCB, 2025). Bottom ash may be reused in construction if non-hazardous, while fly ash often requires pre-treatment and secure landfilling due to heavy metal content. Proper handling and disposal protocols are necessary to avoid environmental contamination and comply with regulations.

4.4 Energy Recovery Efficiency

Despite RDF calorific values of 2,500–3,500 kcal/kg - higher than mixed MSW - actual plant efficiencies remain low, typically 20–25%, and sometimes even lower (Białowiec, A., et al., 2017; ISWMAW, 2023). Energy losses occur due to furnace heat dissipation, turbine inefficiencies, plant auxiliary consumption, and moisture in feedstock (Table 4). NITI Aayog (2021) highlights that average calorific value of MSW supplied to WtE plants is only 1,100–1,500 kcal/kg, far below the minimum 1,700 kcal/kg required. Better pre-processing and blending are critical to improve recovery and financial viability.

At the OPTOCE pilot (Feb 2024, Jindal Visakhapatnam), net thermal efficiency decreased from 13.8% with 100% MSW to 12.2% with 75% RDF, illustrating the challenges of heterogeneous fuels.

In contrast, a modern dry-process 5-stage preheater–precalciner kiln in India operates at 55–60% thermal efficiency with an energy demand of ~730 kcal/kg clinker (or 3,050 MJ/t), typically fuelled by a mix of coal (4,500-5,000 kcal/kg) and RDF/NRPW (2,500-3,500 kcal/kg) at a 20% TSR. Energy losses are mainly due to stack gases, cooler vent air, shell radiation, moisture in the feed, and false-air ingress.

Table 4: Energy balance in a WtE incineration plant in India (ISWMAW, 2023)

Parameter	MWh/t of waste	Notes
Energy Input	2.5	Energy available in waste
Energy Lost / Consumed	1.96	Heat losses (0.25), turbine losses (1.62), plant auxiliary consumption (0.09)
Net Energy Exported	0.54	Delivered to grid

4.5 Financial Sustainability

Despite support under the National Bioenergy Programme, the levelized cost of electricity (LCOE) from MSW incineration remains higher than coal and solar, leaving projects heavily dependent on tipping fees and firm power purchase agreements (PPAs) for viability. Phase-II funding is budget-constrained, with approvals tied to the availability of central allocations (MNRE BioUrja, 2025).

Profitability hinges on predictable feedstock, stable offtake, and reliable tipping fees; in practice, poor waste quality, regulatory uncertainty, and low energy-recovery efficiency in WtE undermine cash flows. To attract private investment and ensure continuous operation, deploy guaranteed contracts, blended finance, and targeted incentives.

5. Cross-Cutting Barriers Affecting Co-Processing and WtE

5.1 Separation, Collection, and Transport

The diverse nature of plastics makes separation of recyclables from NRPW extremely difficult (Hopewell et al., 2009; Kassab et al., 2023). Lightweight packaging, multilayer laminates, and films are often uneconomical to collect due to their low weight-to-volume ratio. Recyclers reject NRPW, and transporting small volumes becomes prohibitively expensive (Kibria et al., 2023).

5.2 Regulatory and Pricing Gaps

RDF pricing is rarely linked to measurable parameters such as calorific value, chlorine, or ash content (Sharma, R., et al., 2023). Weak financial incentives limit motivation for municipalities and pre-processors to produce high-quality fuel. Inconsistent enforcement of co-processing and WtE guidelines across states adds uncertainty, discouraging private investment and limiting sector-scale growth (CPCB, 2020; ISWMAW, 2023). Clear pricing mechanisms and regulatory alignment are essential to secure predictable supply and investment.

5.3 Environmental Compliance and Public Perception

Variable feedstock composition increases the risk of emissions (dioxins/furans, acid gases) and ash generation (Chyang, S.Y., et al., 2010; CPCB, 2025). Limited real-time monitoring, inconsistent flue-gas treatment, and weak enforcement challenge both sectors. Public opposition - driven by odour, traffic, and perceived health risks - further restricts siting and expansion (CSE, 2020). Stakeholder trust and social licence remain key barriers until monitoring, transparency, and communication improve.

Table 5: Comparison of waste-to-energy incineration and cement kiln co-processing

Parameter	Cement Kiln Co-processing	WtE Incineration
Purpose	Industrial production of clinker with waste as fuel/raw material.	Waste volume reduction + electricity/heat generation.
Temperature	950–2,000 °C (long residence, oxidizing; excellent waste destruction).	850–1,100 °C (risk of incomplete combustion, dioxins if controls weak).
CAPEX	~USD 0.6 million (annualized) for 50,000 t/y RDF system. Existing kiln infrastructure.	~USD 2.2 million (annualized) for 6 MW plant (250,000 t/y MSW); ~150-200 million INR/MW.

Parameter	Cement Kiln Co-processing	WtE Incineration
Land requirement	Inside existing plants; minimal extra land.	~5 ha per 1,000 tpd, including buffer zone.
OPEX	~USD 0.8 million/y, transport a major cost driver: USD 1.1-1.6 million/y (300 km).	~ USD 0.95 million/y; high flue-gas cleaning cost. Needs subsidies/feed-in tariffs.
Energy efficiency	60-65% (Theoretical heat ÷ specific heat energy consumption) × 100, using ~440 kcal/kg as the thermodynamic minimum.	15–25% electricity; ~80% with co-generation.
Feed flexibility	Needs dry, low-Cl RDF; limits on moisture/chlorine; pre-processing common.	More versatile; still needs segregation/drying. Wet MSW reduces efficiency.
Residues	None – inorganics locked in clinker.	25–30% residues (bottom + fly ash), fly ash is hazardous, need secure disposal.
Emissions	Comparable to fossil fuel firing if operated well; alkaline raw mix neutralizes acids.	Multiple emission points; strict APC needed. Dioxins/furans risk if poorly managed.
Climate impact	Avoids fossil CO_2 (coal substitution); diverts waste from landfill/ incineration (indirect CO_2 savings).	Fossil CO_2 from plastics; avoids methane from landfill but adds new stacks/ emission points.
Economics	Cost-saving vs coal if RDF priced right; relies on transport/logistics support.	High LCOE (~0.08–0.1 USD/kWh). Only viable with tipping fees, PPAs, subsidies.
Scale / throughput	No minimum; can absorb RDF in proportion to quality/availability.	Needs >300 t/day MSW to be viable.
Social acceptance	Lower profile; integrated in industry. Needs transparency on emissions & product quality.	Often opposed (NIMBY, toxic ash fears); past failures in India reinforce distrust.
Policy fit (India)	Recognized in SWM Rules 2016/2024; CPCB RDF guidelines; supports Net Zero & circular economy.	Subsidized as renewable (biogenic share); but poor track record in Indian cities.
Best use case	Dry, non-recyclable plastics/NRPW within 100-300 km of plants; complement to recycling.	Large cities with steady waste streams + robust APC and energy demand.

Sources: Bhatiani et al. (2023); CSE (2020); NITI Aayog (2021).

Notes to the table:

Waste profile: India's MSW is ~50-60% organic, low calorific (1,500–2,100 kcal/kg). This weakens WtE viability unless pre-treated. Co-processing targets the dry NRPW fraction (plastics, multilayer packaging).

International vs India: EU/Japan achieve 50–60% TSR in kilns and rely on WtE for urban waste (high landfill taxes, strict monitoring). India averages ~5-6% TSR, with leading plants >20%. Most Indian WtE plants underperform due to wet feed and high costs.

Climate lens: WtE helps avoid methane from landfills but adds to additional emission points. Co-processing directly displaces coal and integrates mineral residues into clinker, giving higher CO_2 savings per tonne of NRPW treated.

Policy relevance: India's SWM Rules mandate RDF use within 400 km of cement plants, and EPR/Green Bond financing can scale hubs. WtE may remain niche for mega-cities, but co-processing offers faster, cheaper scaling for NRPW management.

5.4 Data Gaps and Traceability

Limited mass-balance tracking and weak documentation from waste generator to plant reduce transparency and complicate performance verification (Dhodapkar, R., et al., 2023). Traceability is critical for emissions reporting, feedstock assurance, and integration with extended producer responsibility (EPR) programs. Absence of digital tracking or batch-level quality data undermines accountability, slowing sector-scale deployment.

6. Unlocking the Potential of Co-Processing and WtE: Overcoming Barriers

Cement Kiln Co-Processing

6.1 Evidence from India: OPTOCE Pilot Results (2022–2024)

Pilots at Ambuja Bhatapara, Dalmia Dalmiapuram, and JSW Nandyal achieved TSR 10–30%, enabling 339,450 t/yr of NRPW to be co-processed, saving 178,410 t/yr of coal and cutting 430,000 t CO_2/yr. Dioxin emissions (PCDD/F 0.0016–0.015 ng I-TEQ/Nm^3) were far below the 0.1 ng limit, and other pollutants (HCl, TOC, PM, SO_2, heavy metals) remained within MoEFCC standards, confirming safe, stable kiln operations. By contrast, a Vizag WtE pilot (mixed MSW/RDF) met ELVs but delivered only 12–14% net electrical efficiency and produced 28.5% residues. SINTEF's white paper for MoEFCC evaluates India's NRPW management, drawing on OPTOCE pilot evidence, benchmarking co-processing vs. WtE on environmental and economic performance against global best practice; public launch slated for December 2025.

6.2 Scaling Potential of Kilns: TSR and Cost Advantage

Raising sector-wide TSR from ~5% to 15% would displace several million tonnes of coal annually (plant-by-plant computation advised), with marginal capex compared to new WtE builds. A SINTEF–RTI study estimated the cost of co-processing RDF in cement kilns at USD 16–25 per tonne (including Capex and Opex for RDF production and use in kilns, plus 300 km transport, minus the benefit of coal substitution). In comparison, using RDF in Waste-to-Energy (WtE) incineration for electricity generation costs about USD 62 per tonne (Bhatiani et al., 2023).

6.3 Energy Arithmetic: Coal Displacement per Tonne RDF

Per tonne of dry, low-chlorine RDF (~3,500 kcal/kg), kiln co-processing displaces ~0.7 t coal (assuming coal at 5,000 kcal/kg). The same RDF in a WtE plant at ~20% net efficiency offsets ~0.4 t coal (coal power at 35% efficiency). Co-processing thus delivers ~1.7–1.8× the fossil-fuel displacement per tonne of quality RDF.

6.4 Comparative Takeaway: Complementary Roles

WtE helps large cities handle mixed waste quickly. Co-processing delivers larger, cheaper coal avoidance per tonne of dry, spec-compliant NRPW – if municipalities supply consistent RDF at predictable prices and volumes. Used together, they form complementary pillars of end-of-life management.

6.5 What Must Change: System Reforms and Enablers

Quality-linked RDF pricing should reward higher calorific value and low chlorine while penalizing wet or inert fractions. This must be supported by investments in pre-processing infrastructure such as drying, advanced sorting, and blending, alongside enforcement of national specifications. Robust monitoring aligned with Best Available Techniques (BAT) and Best Environmental Practices (BEP) is essential, including continuous emissions monitoring, strict input controls, and clear feed-point rules. Finally, co-processing and other technologies should be embedded within a broader circular economy framework - prioritizing reduction, redesign, and recycling - while aligning with Extended Producer Responsibility (EPR) to ensure a steady supply of feedstock.

7. Policy and Implementation Roadmap for NRPW Management (2025–2035)

India's non-recyclable plastic waste (NRPW) challenge requires more than technology. Effective scale-up of co-processing and WtE depends on policy clarity, a level regulatory and economic playing field, fuel quality assurance, robust infrastructure, and financial mechanisms. The following priorities outline a pragmatic roadmap for 2026–2035.

7.1 Enhance Alternative Fuel Quality Standards

- Implement RDF Quality Standards: Enforce CPHEEO guidelines (Table 6) specifying moisture (<20%), chlorine (<1%), calorific value, and particle size to ensure consistent high-quality RDF supply for kilns and WtE plants (CPHEEO, 2018).

- Certification Protocols: Establish nationwide testing and accredited laboratory certification to guarantee calorific value and low contaminant levels, building confidence among operators.
- Landfill Ban Enforcement: Landfill diversion of high-calorific-value waste (>1,500 kcal/kg) should be mandated nationwide, with penalties for non-compliance. International experience (e.g., Poland, Germany) shows that bans on landfilling high-CV waste significantly improve recovery rates (EEA, 2023).
- Waste Acceptance Protocols & Feed-Point Controls: Require standardized QA/QC and sampling, with plant-level pre-acceptance analysis (CV, moisture, chlorine, ash, heavy metals) and clear rejection criteria. Define feed-point rules by waste class (e.g., VOC-rich/hazardous only at high-temperature zones; prohibit cold-end feeding) and set chlorine input thresholds with documented bypass activation where installed.

Table 6: RDF standards recommended by the Expert Committee (CPHEEO, 2018)

SN	Parameters	Segregated Combustible Fraction (SCF)	RDF - Grade III	RDF - Grade II	RDF -Grade I
1	**Intended Use** [1]	Input for the WtE plant or RDF pre- processing facility	For co-processing directly or further processing	For direct co-processing in cement kiln	For direct co-processing in cement kiln
2	**Size**	< 400 mm [2]	<50 mm or < 20 mm depending upon use in in-line or separate-line calciners, respectively		
3	**Ash**	<20 % [3]	<15 %	<10 %	<10 %
4	**Moisture**	<35 %	< 20%	<15 %	<10%
5	**Chlorine**	< 1.0 % [3]	< 1.0 %	< 0.7	< 0.5
6	**Sulphur**	<1.5 % [3]	<1.5 %		
7	**Net Calorific Value (NCV)**[4]	> 1500 kcal/kg	>3000 kcal/kg	>3750 kcal/kg	> 4500 kcal/kg
8	**Any other parameter**	Odour control [5]	Odour control	Odour control	Odour control

Note to the table:

1. RDF standard: to be mutually decided by ULBs, cement, and other industries.
2. Size >400 mm: requires agreement between ULB/SCF supplier and cement plants.
3. Blending process: deviations in ash, chlorine, and sulphur can be accepted if agreed between ULB/SCF supplier and cement plants.
4. NCV variation: bandwidth to be decided between RDF manufacturer and cement plants; NCV considered as average per consignment.
5. Odour: no quantitative figure provided, as measurement is subjective and equipment is lacking.

7.2 Implement Digital Waste Tracking and Strengthen Enforcement

- Advanced Tracking: Deploy Artificial Intelligence (AI), Internet of Things (IoT) sensors, Quick Response (QR) codes, and blockchain to trace plastics from source to end-use, improving transparency and reducing unsafe disposal.
- EPR Integration: Link tracking systems to EPR reporting platforms for real-time verification of waste collection and processing.
- Incentivize Over-Performance: Reward producers exceeding legal collection or co-processing targets with tradable credits or tax rebates, promoting innovation and covering additional costs (Jinagouda & Sharma, 2025).

7.3 Adopt Quality-Linked Pricing and Fiscal Incentives

- RDF Pricing Mechanism: Index RDF prices to calorific value, chlorine, and ash content to incentivize high-quality fuel supply.

- Discourage Landfilling via Economic Instruments: Increase tipping fees or landfill taxes to make disposal less attractive than recovery. Experience from Flanders (Belgium) shows such measures reduce landfill to ~1% (CEWEP, 2021; EEA, 2023).
- Subsidies and Fiscal Tools for Co-Processing: Offer capital grants, tax breaks, or GST reductions for high TSR or infrastructure upgrades. Leverage EPR funds to support co-processing facilities. Specific fiscal tools should include tipping fee structures aligned with actual operational costs and tax credits tied directly to TSR improvements. Linking TSR performance to carbon credit monetization can also provide steady revenue streams to cement companies investing in co-processing.
- Cost-Recovery & Shared Financing Models: The RTI–SINTEF study (Bhatiani, 2023) evaluated four cost recovery mechanisms for RDF/SCF management, emphasizing the Polluter Pays Principle. The analysis showed that co-processing in cement kilns remains far more cost-effective than WtE, with annualized costs of ~INR 1,324/t RDF versus ~INR 5,162/t for incineration. Recovery options include passing costs through modest cement price increases (~INR 2.5/bag), household waste charges (~INR 18/month), or property surcharges (~INR 4/1,000 sq.ft./month). An alternative is spreading costs via electricity tariffs for WtE (~INR 0.11/kWh). While all approaches recover costs at relatively modest per-unit rates, co-processing models are more viable given their lower CAPEX/OPEX and coal savings (Table 7). Integrating these cost-sharing models with long-term offtake contracts, transparent tipping fees, and green finance can make RDF supply chains financially sustainable.

Table 7: Cost Recovery Models for India (RTI–SINTEF Study, Bhatiani et al, 2023)

Model	**1. Cement Price Increase**	**2. Household Waste Charge**	**3. Property Surcharge**	**4. Electricity Tariff (WtE)**
Mechanism	Pass RDF costs via cement bag price	Flat monthly charge per household	Surcharge on property area	Spread cost via power tariffs
Key Assumptions	Grade III RDF; 51,000 t/y; RDF transported to cement plant (300 km away)	315,000 households; same RDF assumptions as Model 1	1,276m sq.ft. built-up area; same RDF assumptions	6 MW WtE plant; 2,543 GWh annual consumption
Annualized Cost	INR 67.5 million (INR 1,324/t RDF)	INR 67.5 million (INR 1,324/t RDF)	INR 67.5 million (INR 1,324/t RDF)	INR 263.3 million (INR 5,162/t RDF)
Cost to Customer	+INR 2.5 per 50-kg bag (~0.75%)	INR 18/month (~INR 220/year)	INR 4/1,000 sq.ft./month (<INR 50/year)	+INR 0.11/kWh
Key Insights	Straightforward, modest increase, feasible if industry wide.	Equitable, but requires enforcement and ability-to-pay safeguards.	Progressive, links waste to property size, politically feasible.	Highest cost; viable only with subsidies, large urban demand.

Note: Models 1–3 assume RDF facilities are located near cities to minimize transport costs. Alternatively, they can be sited near cement plants, where land is easier to secure but transportation costs are higher; annualized at INR 2,116/t or USD 25/t, compared with INR 1,324/t or USD 16/t, (as shown in the table).

7.4 Use Outcome-Based Permitting

- Fast-Track Permits: Reward low-emission, high-recovery facilities with expedited approvals to incentivize investment in advanced technologies.
- Continuous Emission Monitoring: Mandate CEMS for PM, NO_x, SO_2, HCl, and other pollutants, with public disclosure to drive transparency and compliance.
- Phased Alignment with Global Best Practices: Introduce a phased roadmap to align Indian

emission standards for NO_x, SO_2, PM, and TOC with stricter EU benchmarks, ensuring industry has a clear adaptation timeline while progressively reducing environmental risks.

- BAT Enforcement: Require adoption of dust collection, NO_x controls, SNCR systems, and retrofits per international BAT standards, including periodic audits.
- Independent Audits: Conduct third-party inspections to verify TSR and emission performance; exemplary compliance may earn extended permit tenures or public recognition.
- SOPs, Interlocks & Emergency Preparedness: Mandate plant-specific SOPs (including no-feed rules during start-up/shutdown), automated interlocks tied to kiln O_2/CO/temperature to cut AFR during instability, documented risk assessments, and emergency response plans with worker H&S training and periodic drills.

7.5 Invest in Capacity Building and Infrastructure

- Regional Waste Processing Hubs: Develop sorting, drying, and shredding facilities near urban centres for high-calorific waste. Hubs reduce logistics costs and ensure reliable RDF supply to nearby cement clusters. Public-private partnerships can fund operations.
- Upgrade Cement Plant Capabilities: Retrofit kilns with feeding systems, storage silos, and chlorine bypass systems for safe processing of high-chlorine RDF, preserving clinker quality.
- Mobilize Finance via EPR and Green Funds: Use EPR funds, green bonds, climate finance, and viability gap funding to support RDF hubs and co-processing retrofits, reducing upfront costs for ULBs and private operators/industries. Explore concessional finance instruments to accelerate infrastructure expansion.
- Pilot ULB-to-Cement Supply Chains: Implement pilot projects connecting cities and cement plants to formalize RDF supply chains and identify operational bottlenecks for regional scaling. Partnerships with international agencies can demonstrate best practices and build confidence in replication.
- Training, E-Learning, and Public Awareness: Capacity building for municipalities should go beyond technical training to include community awareness campaigns on waste segregation and simple e-learning modules for local officials. Train municipal officers, plant engineers, and workers in RDF handling, segregation, and fuel testing. Public campaigns improve upstream participation, enhancing fuel quality for co-processing. Complement training with demonstration projects that transparently share emission results and clinker quality tests, showcasing safety and building acceptance.

7.6 Integrated Waste Management Planning

- National Coordination Committee: Establish an inter-ministerial task force including MoHUA, MoEFCC, CPCB, cement industry, and ULBs to harmonize policies, set targets, and monitor WtE and co-processing initiatives. A dedicated national coordination committee should also guide zoning and resource allocation to maximize complementarity between WtE and co-processing.
- Regional Waste Allocation: Map waste streams to facilities based on calorific value, moisture, and proximity, ensuring high-calorific fractions go to cement kilns and lower-calorific or wet waste to WtE or composting.
- Residue Management: Implement ash and by-product handling protocols for WtE and co-processing to minimize environmental risks, including safe disposal guidelines for WtE residues and chlorine bypass dust from cement kilns.
- LCA and Legacy Waste Mining: Mandate LCAs to compare environmental impacts of RDF utilization in kilns versus WtE plants, ensuring siting decisions reflect both economic and environmental efficiency. For guidance on life-cycle assessment and legacy dump remediation strategies, refer to Chapter 7.

Table 8: Recommendations from the RDF Expert Committee (CPHEEO, 2018)

SN	Recommendations	Responsibility
1	Cement plants within 400 km of an RDF facility must use RDF/SCF to replace at least 15% of fuel within 3 years of rule amendment, subject to availability (phased). Transport up to 100 km borne by cement plant; beyond 100 km, cost shared with Urban Local Bodies (ULBs) as agreed.	Ministry of Environment, Forest and Climate Change (MoEFCC)

SN	Recommendations	Responsibility
2	ULBs to mobilize investment directly or via private firms through bidding. Funds from Swachh Bharat Mission (SBM) may be used as Viability Gap Funding (VGF)/grant.	Ministry of Housing and Urban Affairs (MoHUA) through ULBs
3	Prepare Model Tender Documents and tripartite agreements between ULBs, RDF/SCF producers, and cement plants (using Annexure I of Guidelines).	ULBs
4	Cement plants/WtE plants to lift RDF/SCF under mutually agreed terms. Payment by cement plants to ULBs based on calorific value and quality, aligned with guideline benchmarks.	ULBs and Cement Plants
5	To diversify RDF use, MoHUA may support R&D for converting RDF into liquid/solid/gas fuels via 2–3 pilot plants under SBM or with Department of Science and Technology (DST).	MoHUA through SBM / DST
6	For AFR/RDF standardization and wider use, cement manufacturers, National Council for Cement and Building Materials (NCCBM), and Department for Promotion of Industry and Internal Trade (DPIIT, earlier DIPP) should collaborate on R&D.	Ministry of Commerce and Industry (MoCI) and Ministry of Heavy Industries (MoHI, earlier MoHIPE)
7	To promote RDF uptake, industries/ULBs may treat transport costs beyond 100 km (per SN 1) as eligible under Corporate Social Responsibility (CSR) expenses in line with Section 135 of the Companies Act, 2013.	MoHI (earlier MoHIPE) / DPIIT

Table 9: Relationship Matrix of Challenges, Unlocks, and Solutions

Challenge (India context)	What it blocks (impact)	What unlocks potential	Solutions & sequencing (Now → 6–12 mo → 1–3 yr)	Lead / Partners	Decision KPIs
Inconsistent RDF quality (high moisture, chlorine, ash; variable CV)	Stable TSR, emissions compliance, kiln uptime	Spec-grade RDF with QA/QC at source	Now: enforce CPHEEO specs; on-site QA, rejection rules 6–12 mo: install drying, optical sorting, blending 1–3 yr: statewide third-party certification	MoHUA/ ULBs, CPCB, Cement cos., labs	% consignments meeting spec; avg moisture/Cl; TSR trend
Limited pre-processing capacity (MRF/MBT/bio-drying gaps)	Volume throughput; predictable kiln supply	Regional RDF hubs near waste & kiln clusters	Now: identify hubs; VGF/EPR pipeline 6–12 mo: commission 2–3 hubs 1–3 yr: expand to all priority clusters	ULBs, private operators, cement clusters, DFIs	Hub tonnage; km to kiln; INR/t RDF
Misaligned pricing & weak enforcement (RDF not priced by quality)	Investment case for quality upgrades	Quality-linked RDF pricing & contracts	Now: index contracts to CV/Cl/ash 6–12 mo: model tariff bands; publish guidance 1–3 yr: Use the EPR platform for verification and payouts	CPCB/ EPR cell, MoHUA, ULBs, cement cos.	Avg price by grade; floor tonnage with payment guaranteed; EPR payout tied to quality
Emissions oversight gaps (limited CEMS, uneven APC)	Social license; regulatory certainty	Continuous monitoring with disclosure	Now: mandate CEMS (kilns & WtE), SOPs/interlocks 6–12 mo: public dashboards fully implemented 1–3 yr: phased EU-aligned ELVs	CPCB/ SPCBs, plants, IT vendors	% plants on CEMS; hours above the legal limit; public dashboard uptime

Challenge (India context)	What it blocks (impact)	What unlocks potential	Solutions & sequencing (Now → 6–12 mo → 1–3 yr)	Lead / Partners	Decision KPIs
Public trust & siting risk (NIMBY; legacy WtE issues)	Permitting; steady operations	Transparency + local benefits	Now: publish emissions & clinker tests 6–12 mo: grievance/benefit plans 1–3 yr: annual third-party audits & townhalls	ULBs, operators, community representatives	Community acceptance index; audit pass rate
Kiln hardware constraints (feeding points, storage, Cl-bypass)	Higher TSR; chlorine control	Targeted retrofits and SOPs	Now: feed-point rules; cold-end no-feed 6–12 mo: install moving floors, weigh feeders 1–3 yr: chlorine bypass where justified	Cement companies, OEMs, lenders	Capex executed; TSR improved; kiln stability (trips/1,000 t)
Logistics cost/distance (100–300 km corridors)	Delivered cost; reliability	Corridor planning & backhaul	Now: MoUs on backhaul; route optimization 6–12 mo: cluster contracts 1–3 yr: multimodal pilots	ULBs, cement clusters, 3PLs	Delivered INR/t; on-time delivery %
Finance gap / bankability (esp. hubs, retrofits)	Scale-up of capacity	Blended finance using EPR/green funds	Now: standard term-sheets; viability-gap toolkit 6–12 mo: first pooled EPR + green bond deals 1–3 yr: pay-for-performance (TSR/LCA)	MoHUA, CPCB, DFIs, banks	Fund mobilized; cost of capital; projects reaching financial close.
Data gaps & traceability (mass balance, EPR proof)	Crediting under EPR; integrity	Digital tracking (AI/QR/IoT; batch QC)	Now: minimal datasets & QR on consignments 6–12 mo: integrate with EPR portals 1–3 yr: real-time chain-of-custody	CPCB/ EPR cell, IT providers, operators	% tracked tonnes; audit discrepancies reduced.
WtE: wet MSW / low CV & residues (12–25% net eff.; 25–30% ash)	Power yield; ash burden	Pre-treatment + right-sizing	Now: enforce front-end MBT/bio-drying 6–12 mo: co-fire RDF in boilers seasonally 1–3 yr: CHP where heat sinks exist	WtE operators, ULBs, state utilities	Net kWh/t; residue rate %; PLF.

Notes: 3PLs: Third-Party Logistics providers; CHP: Combined Heat and Power; DFIs: Development Finance Institutions; MBT: Mechanical–Biological Treatment; MRF: Material Recovery Facility; NIMBY: Not in My Back Yard; OEMs: Original Equipment Manufacturers; PLF: Plant Load Factor; QA/QC: Quality Assurance/ Quality Control; VGF: Viability Gap Funding.

8. Regional Deployment Strategies

8.1 Metro Regions (Large Cities): Integrated Waste Hubs

Metropolitan areas such as Delhi, Mumbai, and Bengaluru should prioritize integrated waste hubs that combine material recovery facilities (MRFs), composting units, WtE incineration, and RDF production. Centralizing segregation and processing reduces landfill volumes, ensures efficient energy recovery, and enables reliable RDF supply for cement kilns. For example, Delhi's MoU with JK Cement (2022) diverts 50,000 t/year of RDF from landfills to co-processing, illustrating how urban waste hubs can achieve landfill diversion while producing energy and recovering materials.

8.2 Cement-Industry Clusters: Connecting Waste to Fuel

Regions with high concentrations of cement plants, such as Tamil Nadu, Andhra Pradesh, Gujarat, and Chhattisgarh, should establish robust waste-to-fuel supply chains. Municipalities and cement plants can formalize agreements ensuring predictable RDF volumes and quality, while regulators can mandate gradual RDF co-processing targets (6–15% of kiln fuel). This approach reduces coal consumption, mitigates emissions, and provides a stable, cost-effective fuel source, mirroring practices in European cement clusters with average TSR of 50%.

8.3 Legacy Dump Sites: Mining and Reclaiming Old Landfills

Legacy dumpsites pose environmental hazards such as leachate, methane emissions, and fires, while occupying valuable land. Biomining or landfill mining can recover combustible fractions, plastics, and RDF for co-processing, simultaneously reducing emissions and reclaiming land. The cost of biomining legacy dumpsites depends on site size and waste volume rather than cubic meters. Processing averages INR750- 900 per tonne, covering manpower and off-site transport, while a 700 tonnes/day mobile unit requires INR 100 million in capital. Operators increasingly use programmable logic systems to manage stabilized waste flow, though moving combustible fractions remains cost-sensitive to the distance from cement plants (CSE, 2020).

8.4 Small Towns and Rural Areas: Cluster-Based Approaches

Smaller towns and rural areas can form regional clusters to achieve sufficient scale for RDF and WtE facilities. Decentralized segregation, small MRFs, and composting units handle organic and recyclable waste locally, while residual plastics are aggregated and sent to nearby cement kilns. For instance, a cluster of 11 ULBs in Bihar supplies a central 15 MW WtE and 250 tonnes/day RDF facility, processing 1,600 tonnes/day of municipal waste efficiently, achieving economies of scale and reducing landfill reliance (Sharma et al., 2025).

8.5 Transport and Logistics Optimization

Efficient logistics are critical to ensure timely RDF delivery to cement kilns or WtE plants. Strategies such as backhauling trucks - carrying segregated waste on return trips from cement plants or material supply routes - reduce transport costs, minimize empty journeys, and ensure consistent fuel supply. Properly designed regional transport networks strengthen public-private partnerships, stabilize RDF supply chains, and improve overall financial and operational viability of both co-processing and WtE projects.

8.6 Life-Cycle Assessment (LCA) and Decision Support

All regional deployment plans should integrate life-cycle assessment (LCA) to compare environmental and energy impacts of WtE versus kiln co-processing. LCA accounts for transport distances, greenhouse gas emissions, energy recovery, and residue management, enabling evidence-based planning. For example, a city near multiple cement plants may achieve better energy and CO_2 savings via co-processing rather than investing in new WtE capacity. This ensures infrastructure investments deliver optimal environmental and economic outcomes.

SINTEF’s site-specific LCA in Vapi showed that landfilling CETP sludge had the highest environmental impact and should have been avoided. Incineration without energy recovery also had detrimental impacts due to emissions and additional fuel use, while incineration with energy recovery performed better by offsetting fossil fuels for electricity and heat. Despite long transport distances, co-processing in cement kilns delivered the most sustainable results by replacing fossil fuels and minimizing residual waste. To further reduce transport impacts, solar drying of sludge at source was recommended (Azrague et al., 2019).

9. Conclusion

India possesses abundant non-recyclable plastic waste (NRPW) but lacks consistent, quality-assured recovery pathways. Cement kiln co-processing offers an efficient solution for dry, low-chlorine NRPW, delivering higher energy recovery and coal displacement per tonne, while waste-to-energy (WtE) incineration provides city-scale processing for mixed municipal waste. Both pathways are critical pillars within a circular economy hierarchy, complementing upstream reduction, redesign, and recycling.

Despite regulatory progress - including ELVs, BAT/BEP-aligned emission limits, SOPs, and ongoing legacy dumpsite remediation - challenges remain: inconsistent feedstock quality, limited pre-processing infrastructure, enforcement gaps, and financial uncertainties constrain scale-up. The 2025–2035 policy and implementation roadmap addresses these barriers through RDF quality standards, transparent TSR targets, regional pre-processing hubs, outcome-based permitting, digital EPR-linked tracking, fiscal incentives, and capacity-building initiatives.

By combining regulatory enforcement, market mechanisms, and technical support, India can unlock the full potential of co-processing and WtE, reduce landfill dependence, minimize greenhouse gas emissions, and enhance financial viability for private and public stakeholders, cementing a transition to a sustainable, circular plastic economy.

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References

Aggarwal, A. (2023). It is critical to lift veil of secrecy around use of refuse-derived fuel in cement plants. *Down to Earth.* https://www.downtoearth.org.in/blog/waste/it-is-critical-to-lift-veil-of-secrecy-around-use-of-refuse-derived-fuel-in-cement-plants-92481

Azrague, k., Saha, P. K., Karstensen, K. H. (2019). Evaluation and comparison of management alternatives for Common Effluent Treatment Plant (CETP) sludge in Vapi, India. *Cement, Energy and Environment*. Volume 18, No. 1, Jan-June 2019.

Bhatiani, G., Karstensen, K. H. and Saha, P. K (2023). Business Models for utilization of non-recyclable plastic in the Indian cement industry. *International Cement Review*. November 2023. ISSN 0959-6038.

Caputo, A. C., & Pelagagge, P. M. (2002). RDF production plants: I. Design and costs. *Applied Thermal Engineering, 22*(4), 423–437. https://doi.org/10.1016/S1359-4311(01)00100-4

Centre for Science and Environment (CSE). (2020). Clean it Right: Dumpsite Management in India.

Chyang, S.-Y., Han, Y.-L., Wu, L.-W., Wan, H.-P., Lee, H.-T., & Chang, Y.-H. (2010). An investigation on pollutant emissions from co-firing of RDF and coal. *Waste Management, 30*(7), 1334–1340. https://doi.org/10.1016/j.wasman.2009.11.018

Central Pollution Control Board (CPCB). (2020). Annual Report 2020–21 on Implementation of Plastic Waste Management Rules.

Central Pollution Control Board (CPCB). (2021). Compliance Report of Waste to Energy Plants in Delhi.

Central Pollution Control Board (CPCB). (2025). Guidelines on Municipal Solid Waste (MSW) Incineration Based Waste-to-Energy Plants.

Central Pollution Control Board (CPCB). (2025). Municipal Solid Waste Management Rules Compliance Report.

Central Public Health and Environmental Engineering Organisation (CPHEEO). (2018). Guidelines on usage of refuse derived fuel in various industries. Ministry of Housing and Urban Affairs, Government of India. https://sbmurban.org/storage/app/media/pdf/SBM%20RDF%20Guidelines.pdf

CEWEP. (2021). Overview of landfill taxes and bans in Europe. Brussels: CEWEP. https://www.cewep.eu/wp-content/uploads/2021/10/Landfill-taxes-and-restrictions-overview.pdf

Cottom, J.W., Cook, E. & Velis, C.A., 2024. "A Local-to-Global Emissions Inventory of Macroplastic Pollution." *Nature*, 633, 101–108 (2024). https://doi.org/10.1038/s41586-024-07758-6.

Dhodapkar, R., Bhattacharjya, S., Niazi, Z., Porter, N. B., Retamal, M., Sahajwalla, V., & Schandl, H. (2023). National Circular Economy Roadmap for Reducing Plastic Waste in India. CSIRO.

European Environment Agency (EEA). (2023). Economic instruments and separate collection systems — key strategies to increase recycling. Briefing published on 08 Jun 2023. https://www.eea.europa.eu/en/analysis/publications/economic-instruments-and-separate-collection Accessed on 18 September 2025.

GCCA/TERI. (2025). Decarbonization Roadmap for the Indian Cement Sector: Net Zero CO_2 by 2070.

Geyer, R., Jambeck, J.R., & Law, K.L., 2017. "Production, Use, and Fate of All Plastics Ever Made." *Science Advances*, 3(7), e1700782.

, S. K., Parlikar, U. V., Karstensen, K. H. (2022), Sustainable Management of Wastes through Co-processing, Book, Springer Nature Singapore Pte Ltd. 2022; https://doi.org/10.1007/978-981-16-6073-3

Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastics recycling: Challenges and opportunities. *Philosophical Transactions of the Royal Society B, 364,* 2115–2126. https://doi.org/10.1098/rstb.2008.0311

India Plastics Pact. (2022). Landscape Assessment of Plastic Recycling in India. IPP Landscape Assessment Report_Web Accessed on 20 September 2025.

Indian Society of Waste Management, Air and Water (ISWMAW). (2023). Assessment of non-recyclable plastic waste (NRPW) management pathways in India.

Jinagouda, P., & Sharma, A. (2025). EPR as an accelerator for circular economy in India's plastic waste management industry: A systematic review. *Journal of Informatics Education and Research, 5*(2), 704–728.

Kapur-Bakshi, S., Kaur, M., and Gautam, S., 2021. Circular Economy for Plastics in India: A Roadmap. New Delhi: The Energy and Resources Institute.

Karstensen, K. H., Saha, P. K. (2016). India's coal coup. *International Cement Review.* January 2016. ISSN 0959-6038.

Karstensen, K. H., Parlikar, U. V., Ahuja, D., Sharma, S., Chakraborty, M. A., Maurya, H. P., Mallik, M., Gupta, P. K., Kamyotra, J. S., Bala, S. S., Kapadia, B. V. (2014), Destruction of concentrated Chlorofluorocarbons in India demonstrates an effective option to simultaneously curb climate change and ozone depletion. *Environmental Science and Policy*, 38 (2014) 237-244. ISSN No. 1462–9011.

Kassab, A., Al Nabhani, D., Mohanty, P., Pannier, C., & Ayoub, G. Y. (2023). Advancing plastic recycling: Challenges and opportunities in the integration of 3D printing and distributed recycling for a circular economy. *Polymers, 15*(19), 3881. https://doi.org/10.3390/polym15193881

Kibria, M. G., Masuk, N. I., Safayet, R., Nguyen, H. Q., & Mourshed, M. (2023). Plastic waste: Challenges and opportunities to mitigate pollution and effective management. *International Journal of Environmental Research, 17*(1), 20. https://doi.org/10.1007/s41742-023-00507-z

Kvale, K., Azimrayat Andrews, Z., & Egger, M. (2024). "Mind the Fragmentation Gap." *Nature*.

Lázár, M., Čarnogurská, M., Lengyelová, M., & Korba, J. (2015). High-temperature gasification of RDF waste and melting of fly ash obtained from the incineration of municipal waste. *Acta Polytechnica, 55*(1), 1–6. https://doi.org/10.14311/AP.2015.55.0001

Ministry of Housing and Urban Affairs (MoHUA), Swachh Bharat Mission- Urban: Legacy Waste Management Dashboard. https://sbmurban.org/swachh-bharat-mission-progess Accessed on 19 September 2025.

MNRE BioUrja. (2025). National Bioenergy Programme. Ministry of New and Renewable Energy, India.

NITI Aayog. (2021). Waste to Energy: Status and strategies for India. National Institution for Transforming India, Government of India.

Saha, P. K., Karstensen, K. H., Vigerust, E. L., Balakumar, V., Bhatiani, G. (2020), India's current and potential MSW use in RDF production, *International Cement* Review, October 2020, ISSN 0959-6038.

Sharma, P., Kukreja, K., Reddy, K. P. K., Mittal, A., Panda, D. K., & Mohapatra, B. (2023). Refuse derived fuel (RDF) co-processing in kiln main burner in a cement plant: A case study. In *Proceedings of International Conference on Advances in Sustainable Construction Materials and Civil Engineering Systems* (pp. 331–339). Springer. https://doi.org/10.1007/978-981-99-2279-6_28

Sharma, U., Kumar, A., & Singh, M. (2025). Refuse-derived fuel production and utilization potential from municipal solid waste in India. *Science of The Total Environment.*

Singh, R. (2024). Gainful utilization of segregated combustible fraction (SCF) recovered from biomining of legacy waste dumpsites in India. Centre for Science and Environment, New Delhi.

Wan, Y., et al. (2008). Slagging and fouling in municipal solid waste incinerators. *Waste Management, 28*(8), 1442–1451.

Comparative Study on Performance of Bacterio-algal Fuel Cell with and without Biofilm

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ABSTRACT

Microbial Fuel Cells (MFCs) convert chemical energy stored in organic carbon sources to electricity using exo-electrogens. In Bacterio-algal Fuel Cell (BAFC), algae are used in the cathode chamber to assimilate CO2 produced in anode chamber and produce oxygen required for cathode reaction. The present article focuses on the performance of a batch type BAFC using lactic acid as substrate and clay as PEM instead of expensive Nafion. Exoelectrogen, Shewanella putrefaciens MTCC 8104 and cyanobacterium, Leptolyngbya subtilis JUCHE1 have been used in the anode and cathode chambers respectively. The volumes of the anode and cathode chambers are 150mL and 700mL respectively and carbon cloth has been used as anode and cathode material. The BAFC has been run for 120h with the concentration of substrate being 3g/L with and without biofilm of Shewanella putrefaciens MTCC 8104. The maximum current of 37µA and coulombic efficiency of 5.91% have been obtained for the BAFC, run without biofilm, using the substrate concentration of 3g/L. Using biofilm, the peak operating current and coulombic efficiency reach the value of 230 µA and 33.06% respectively. The cyclic voltammograms of biofilm systems also show efficient charge transfer as compared to that using suspended culture in the anode chamber. This study introduces the novel approach for applying biofilm alongside the usage of algal strain on cathode side of MFC. Results successfully demonstrate the effectiveness of the proposed strategy based on improved electron transfer and power output, paving way for further upgradation of the system based on mode and scaling up.

Keywords: Proton Exchange Membrane, Dual-chambered Bacterio-algal Fuel Cell, Leptolyngbya subtilis JUCHE1, Shewanella putrefaciens MTCC 8104, Biofilm.

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1. Introduction

Energy demands have been increasing day by day along with the gradual decline in conventional energy sources. Transition from conventional to renewable energy sources seems inevitable to address the ever-declining trend of conventional fuels and to protect the environment. Bioenergy is expected to play a vital role in the progressive energy transition. Upcoming bioenergy technologies, including bio-electrochemical systems (BESs) such as microbial fuel cells (MFCs), microbial electrolysis cells (MECs) (Wei et al., 2022b; Ramanaiah et al., 2023), microbial desalination cells (MDCs), etc., for energy generation using renewable sources have become one of the main areas of focus for researchers currently. Bioelectricity generation by a MFC (Fang et al., 2014; Kim et al., 2002; Zhang et al., 2021) using wastewater is such an approach of bio-energy generation through exploitation of microbial metabolism. Though MFC is a promising technology considering the goals of renewability and sustainability, it cannot mitigate carbon dioxide emissions fully because the microbial reaction occurring in the anode generates CO_2 as a product (Gadhamshetty et al., 2012). A BAFC, developed by using anaerobic culture of electroactive bacterial strains in the anode chamber and algal cultivation in the cathode chamber, can avoid the CO_2 emission issue. (Nishio et al., 2012; Liu et al., 2015; Aiyer., 2021) A BAFC is capable of converting chemical energy stored in biodegradable organic wastes (Marassi et al., 2021; Yaakop et al., 2023; Chaudhary et al., 2023) into electrical energy while simultaneously ensuring the treatment of wastewater along with bio-capturing and utilisation of the generated CO_2. Other than ensuring the CO_2 sequestration, the algal culture in the cathode compartment also serves as the continuous source of O_2, formed through the photosynthesis reaction. This minimizes the cost involved in providing either external aeration or usage of external electron acceptor like ferricyanide etc., as used in conventional MFCs (Ucar et al., 2017). In addition, algal biomass produced in the cathode chamber can be used as a source of biofuels and biochemicals (Bhatia et al., 2022b). Moreover, the algal solid residue remaining after the extraction of lipid and pigments can be used in the anode as a carbon source (Mahmoud et al., 2021; Xu et al., 2019). Conventionally, in a dual chambered Bacterio-algal fuel cell (DC-BAFC), suspended cultures of both the electroactive bacterial strain and the algal strain are respectively used in the anode and cathode chambers. As the efficiency of the MFCs depends on the ease of electron transfer to the anode, it has been reported that the use of bacterial biofilm on the anode improves the electrical performance of the cell due to direct electron transfer (Mukherjee et al., 2021). Similarly, the application of algal biofilm on the cathode chamber has been reported to be beneficial due to direct electron transfer at the cathode (Gajda et al., 2015). Biofilm is the accumulation of microorganisms on any abiotic or biotic surface resulting in formation of a film-like structure (Logroño et al., 2017). A biofilm can be formed by a single species or multiple species acting together as a colony. The cells colonize on the secreted exopolymeric substances, thus forming a slimy layer of biofilm attachment. In recent literature, the performance of four BAFC set-ups implementing algal or bacterial biofilm in two single chambered and two dual chambered systems have been compared (Mahmoud et al., 2021b). They also fed dry, de-oiled, and depigmented algal biomass as substrate to the bacterial culture in the anode chamber. The double chamber fuel cells with bio-cathode generated the highest power density along with the best removal of COD content (Khandelwal et al., 2017). In another report on a microbial desalination cell, it has been claimed that passive algal bio-cathode performs better than air cathode (mixing or mechanical aeration) (Kokabian & Gude, 2013). In spite of extensive research on MFCs, there are still a few areas that remain unexplored. One such area is the loss of electrons due to indirect transfer to the anode. Another unexplored aspect is the replacement of Nafion with some inexpensive material as a proton exchange membrane (PEM). Again, although *Shewanella putrefaciens* is a promising electro-active bacterium, it has been rarely used in bacterio-algal fuel cells (BAFCs). Besides, the continuous supply of oxygen in the cathode chamber poses a problem. While blue-green algal species are highly efficient in CO_2 capture, there is almost no available report on usage of blue-green algae in BAFCs. Moreover, systematic performance analysis of BAFCs using suspended and attached cultures has been rarely reported. Diversification of available sources of wastewater for use in the anode chamber of the BAFC is another unexplored area. For the revelation of the facts related to the change in performance of BAFCs due to the use of biofilm, a comparative study of performance of BAFCs with and without biofilm is needed. However, no such studies on BAFC are available in the literature. The present study mainly focuses on the comparison of performance of DC-BAFC with and without the application of biofilms of both the organisms used in their respective chambers for two combinations: (I) using both bacterial and algal cells in suspension;(II) both cells attached to electrodes. In both the studies, lactic acid has been used as the carbon substrate in order to simulate the wastewater effluent of typical dairy industries (Ye et al., 2022). The performances of BAFCs with and without biofilms are also compared from the perspective of Coulombic efficiency and overall CO_2 avoidance. The dynamics of biofilm for both the bacterial and algal strains have been analyzed. The present study would pave the way for further upgradation of the system based on mode and scaling up. (Lakshmanan et al., 2024; Wang et al., 2023)

2. Materials and Methods

2.1 Inoculation and synthetic wastewater

A pure culture of electrochemically active bacterium, *Shewanella putrefaciens* MTCC 8104 (SP), purchased from Microbial Type Culture Collection, Chandigarh, India (MTCC) (Panda & Chowdhury, 2020), was used as the anode organism. The medium for the anode chamber, i.e., the anolyte, was simulated by adding 30g/L lactic acid (LA) to M-9 medium so that the final concentration of LA was maintained at 3000 ppm. The concentration of LA was chosen on the basis of the data obtained from growth kinetic study of the said organism using LA as substrate (see supplementary information with for Figure S1). The composition of the M-9 medium (1L basis): 75 g di-Potassium hydrogen phosphate (K_2HPO_4); 30 g Potassium di-hydrogen phosphate (KH_2PO_4); Sodium chloride (NaCl)– 5 g, Ammonium chloride (NH_4Cl) – 5 g; Magnesium sulphate ($MgSO_4$) (Merck) – 10 g; Calcium Chloride ($CaCl_2$) – 10 g. Magnesium sulphate and Calcium Chloride were autoclaved separately and were added to sterile aqueous solution containing all other above mentioned salts. On the other hand, the catholyte, i.e., the medium in cathode chamber, was inoculated with a cyanobacterial strain *Leptolyngbya subtilis JUCHE1* (LS). LS was reported to be rich in lipid content and high CO_2 capturing capacity (Das et al., 2020). The cathode chamber was supplied with 300 mL of M-18 medium, saturated with 100% pure carbon dioxide gas. The composition of M-18 medium (1L basis): having a composition of Sodium nitrate ($NaNO_3$) – 1.5 g/L, Magnesium sulphate heptahydrate ($MgSO_4.7H_2O$) - 0.38 g/L, Di-Potassium hydrogen phosphate (K_2HPO_4) – 0.12 g/L, Calcium chloride di hydrate ($CaCl_2.2H_2O$) – 0.11 g/L, Sodium chloride (NaCl) – 0.07 g/L, Ferric sulphate tetra hydrate ($Fe_2(SO_4)_3.4H_2O$) – 0.01 g/L, Boric acid powder (H_3BO_3) – 0.003 g/L, Manganese sulphate tetra Hydrate ($MnSO_4.4H_2O$) – 0.002 g/L, Zinc sulphate heptahydrate ($ZnSO_4.7H_2O$) – 0.002 g/L, Copper sulphate crystals ($CuSO_4.5H_2O$) – 0.00008 g/L ,cobalt Chloride crystals ($CoCl_2.6H_2O$) – 0.00004 g/L.M-18 medium was first sterilized, and subsequently CO_2 was passed through the sterile medium via an air-filter.

2.2 Biofilm formation

For the pre-formation of bacterial biofilm on the carbon cloth electrode (anode) surface, approximately 30 mL of sterile M-9 medium, as described in Section 2.1, was added to a sterile 50 mL beaker, in which a sterilized piece of carbon cloth (4 cm * 4 cm) was immersed. Finally, 2 mL of SP culture, grown in LB media with an OD of 0.5 at 600 nm, was added as inoculum to the beaker. Seven such beakers were prepared and then sealed with parafilm and aluminium foil, followed by incubation at 37 °C in a B.O.D incubator for 7 days. Samples of biofilm from each beaker were then studied under a microscope for the subsequent 7 days. Another beaker prepared in exactly the same way but without any inoculation was used as a control.

For the pre-formation of algal biofilm on the carbon cloth electrode (cathode), 30 mL of M-18 medium saturated with CO_2, as described in Section 2.1, was added to a sterile 50 mL beaker, in which a sterile piece of carbon cloth (4 cm * 4 cm) was submerged. Finally, 2g of wet algal biomass of LS was added as inoculum to the beaker, which was then sealed with parafilm and incubated in a B.O.D incubator at 37 °C for 7 days. Samples of biofilm from each beaker were then studied under a microscope for the subsequent 7 days. Another beaker prepared in exactly the same way but without any inoculation was used as a control.

The bacterial and algal biofilms formed on the respective electrodes were inspected under a microscope, and the maturation, thickness, and tendency to detach were assessed. Based on the inspection results, a decision was made regarding their use in the BAFC. The decision was made judiciously so that the maturation was sufficient, yet the thickness was such that the diffusion of substrate was not hindered.

2.3 BAFC construction

Two dual-chambered BAFCs named BAFC-S (containing suspensions of the organisms) and BAFC-B (containing biofilm of the organisms) were fabricated for this study as described in Table 1.

Table 1:
Inoculum type for the bacterial and algal strains used in respective chambers of the four BAFCs under study

BAFC system	Inoculum type in anode	Inoculum type in cathode
BAFC-S	Bacterial suspension.	Algal suspension.
BAFC-B	Preformed bacterial biofilm.	Preformed algal biofilm.

Each system was constituted of two concentric cylindrical chambers: an anode chamber made of a cylindrical earthen clay pot (Neethu et al., 2019; Sarma & Mohanty, 2023) (with a total volume of 120 mL) to which 100 mL of simulated wastewater was added, and a cathode chamber made of a PET vessel (with a total volume of 500 mL) filled with 300 mL of M-18 media. The clay wall of the earthen clay pot acted as the proton exchange membrane (PEM) for the transfer of protons from the anode chamber to the cathode chamber, thus alleviating the need for the use of commercially available expensive PEMs like Nafion (Antolini., 2015). A PET pipe was placed in a manner so that one end was open at the headspace of the anode chamber, and the other end was dipped in the algal medium of the cathode chamber for the transfer of the carbon dioxide gas released by anodic bacterial metabolism. This arrangement ensured the assimilation of the produced CO_2 by the algal strain, resulting in oxygen production in the cathode chamber. Both the anode and cathode were made of carbon cloth (4 cm * 4 cm in dimensions), and the electrical wires (20 cm in length) were securely taped to them. Both blank electrodes and ones with preformed biofilms of either organism were placed in their designated chambers, and the open ends of the wires were connected via a 1kΩ resistance to complete the circuit. The daily changes in voltage readings were observed using a digital multimeter. Both the DC-BAFCs were operated in batch mode for 5 days. The systems were initially fed with simulated wastewater containing lactic acid as carbon substrates at the beginning of the operation, and no intermittent feeding was done.

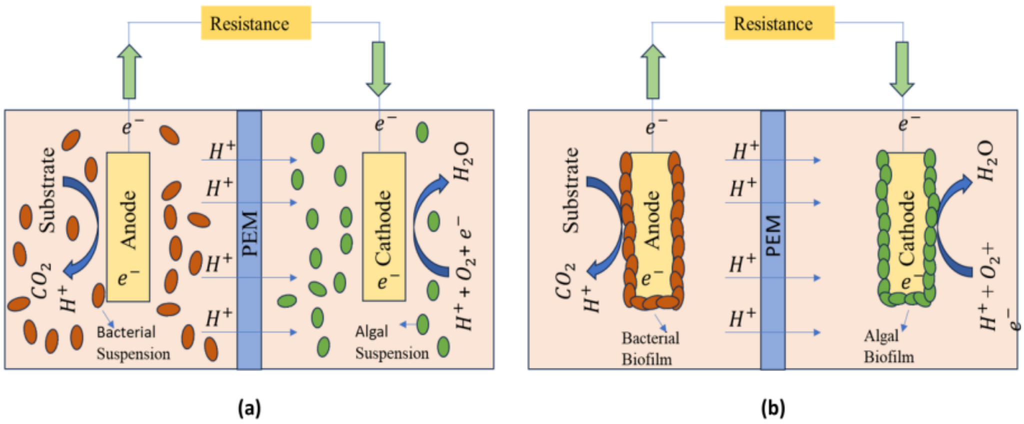


Figure 1. Schematic representation of the 4 types of DC-BAFCs under study (a) BAFC-S (b) BAFC-B.

2.4 Compound Microscopy and Environmental Scanning Electron Microscopy (ESEM)

The biofilm formation dynamics of both strains were observed with the help of a compound microscope on a daily basis for 7 days. The samples were placed on clean slides, then covered with glycerol and finally topped with glass coverslips for observation at 60X magnification.

For ESEM analysis after biofilm development, a small portion of the carbon cloth electrode with an intact portion of biofilm sample on it was cut off and taken out with the help of a pair of sterilized scissors and forceps. The biofilm-electrode sample along with a blank sample, i.e., a portion of bare carbon cloth without any biofilm attachment, was also taken. Both the samples were now put in a 3% glutaraldehyde solution for at least an hour for primary fixation. After one hour, the sample was again carefully taken out and dipped in sterile normal saline water for 5 minutes. Finally, after the fixation was done, the samples were taken out of the saline solution and dipped serially in graded alcohol solutions (30%, 40%, 50%, 75%, 90%, and 100%) alcohol for 5 minutes each. All the glassware used in this procedure was also sterilized using autoclave, and sterile distilled water was used for the solutions. The entire procedure was performed inside the Laminar Air Flow Bench (LAFB). Before gold coating the sample with the help of a sputter coater for making them conductive, the samples were taken out of the 100% ethanol solution and air dried with the help of a dryer to remove any excess moisture. The ESEM analysis was conducted using the sample prepared using the above protocol.

2.5 Electrochemical Analysis (Cyclic Voltammetry)

Electrochemistry is a powerful tool to probe reactions involving electron transfers. It relates the flow of electrons to chemical changes (Elgrishi et al., 2017). In a bacterio-algal fuel cell, the production of energy occurs due to continuous oxidation and reduction of chemical molecules. While oxidation of biomass in the anode compartment results in the production of electrons, the reduction of those electrons in the cathode compartment completes the chemical reaction. This continuous process of chemical changes can be depicted by an electrochemical analysis of both compartments. Cyclic voltammetry is a popular electrochemical technology very commonly used to investigate the reduction and oxidation processes of a chemical reaction. With these specifications, the CV analysis was carried out to examine the peak voltage and peak current obtained from oxidation and reduction occurring with and without the biofilm system.

2.6 Theoretical Analysis and calculations

The output voltage during the entire period of operation of the DC-BAFCs was recorded using a digital multimeter with a regular time interval. Cyclic voltammetry for understanding electrochemical activity was carried out using Potentiostat/Galvanostat (K-Lyte 1.0) where carbon cloth electrodes of the anode and cathode act as working and counter electrodes, while the saturated calomel electrode (SCE) acts as a reference electrode.

2.6.1 Coulombic efficiency

Similar to conventional MFCs, the charge generated in BAFCs is due to the transfer of electrons to the anode. The source of electrons is the carbon source. In reality, a part of the theoretical amount of charge is actually obtained as the output of MFCs, including BAFCs. The coulombic efficiency (E_{cb})is a measure of actual generation of charge by an MFC with respect to the theoretical amount of charge and is defined as follows: (Drapcho et al., 2008)

$$E_{cb} = (C_i/C_m) * 100 \quad (1)$$

Where,
C_i =Actual output charge of BAFC

$$C_i = \int_0^t I_{av}\, dt \quad (2)$$

I_{av}=average of minimum and maximum current, amp;
t = time of operation of BAFC, seconds;
C_m = Charge generated if all theoretically possible number of moles of electrons were transferred.

$$C_m = F * V * C * n \quad (3)$$

Where,
F = Faraday's constant = 96485 Coulomb/mole of electron transferred to anode
V = volume of anode medium, L;
C= molar concentration of carbon source, mole/L;
n= theoretical number of moles of electrons transferred from one mole of carbon source (4 moles of electrons can be supplied from each gram atom of carbon present in one mole of carbon source)

2.6.2 Environmental analysis for BAFCs

Through the generation of energy using MFCs, including BAFCs, CO_2 emissions expected to be reduced in comparison to same amount of grid power, generated in power plants using conventional fossil fuels. Avoidance of CO_2 Emission (%) (ACE) for all BAFCs, developed under the present study, has been determined with reference to CO_2 emission of coal-based power plants in India.

Basis: Energy generated by BAFC for 1 hour operation

$$ACE = \frac{(CO_2\ emission\ by\ coal\ based\ power\ generation) - (CO_2\ emission\ by\ BAFC)}{CO_2\ emission\ by\ coal\ based\ power\ generation} * 100 \quad (4)$$

ACE has been calculated on the basis of 0.01 Wh where Wh = watt-hour of energy from grid and BAFC.
The value of CO_2 emission factor is 0.95kg/kWh for conventional Indian power plant (Mittal et al., 2012),

CO_2 emission by coal-based power generation=0.95 g/Wh * 0.01 Wh= 0.0095g

$$ACE(\%) = \frac{(0.0095g) - (CO_2\ emission\ by\ BAFC)}{0.0095g} * 100 \quad (5)$$

For the BAFC, CO_2 emission is negative because the algal culture in the cathode chamber captures CO_2.

3. Results and Discussions

3.1 Microscopic Analysis of Biofilms

The compound microscopic analysis for the study of the dynamics of biofilm formation has revealed that there was almost no attachment observed on day 1, as shown in Fig. 2(a). Visible attachment has been observed after day 2, and a distinct monolayer of bacterial attachment has been visible on day 3, as depicted in Fig. 2(b). The monolayer gradually started to thicken due to bacterial proliferation into more layers, resulting in the formation of a multilayered bacterial biofilm from the 4th day onwards. A mature, thick multi-layered biofilm has been observed on day 7, as shown in Fig. 2(c). After this stage, difficulty in substrate diffusion to the innermost layer of the bacterial biofilm starts to occur, which ultimately resulted in the commencement of detachment or sloughing off of the bacterial biofilm attachment from the carbon cloth substratum.

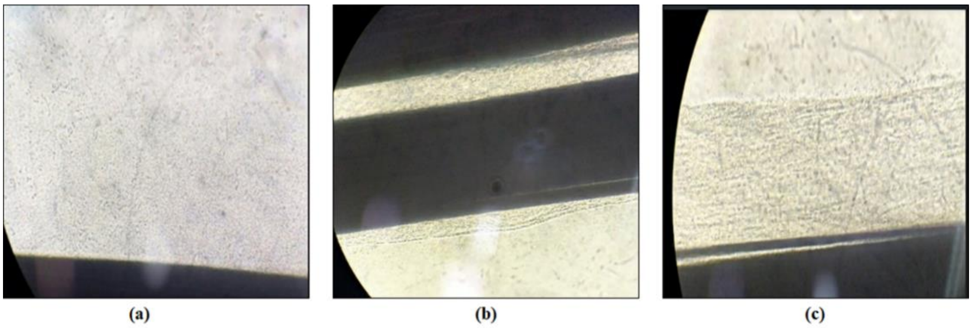


Figure 2. Compound microscopic images of (a) carbon cloth electrode without any attached biofilm; (b) distinct monolayer visible on carbon cloth surface and (c) thick multi-layered biofilm of bacterium *Shewanella putrefaciens* MTCC 8104.

From the SEM analysis, it is evident that SP consists of electrically conductive pili as well as self-developed exopolymeric substances or EPS, which are necessary for electron transfer from substrates and biofilm formation (Panda & Chowdhury., 2020). Under a 600X lens of the microscope, carbon cloth without a bacterial biofilm was observed to have smooth and thin hair-like carbon fibers, perfectly visible in the image shown in Fig. 3(a). Under 6000X magnification, the images of the carbon cloth with attached bacterial biofilm were very distinct. It was evident from the micrographs shown in Fig. 3(b), Fig. 3(c)., and Fig 3(d). that there was a dense attachment of distinctly visible bacteria with conducting nanowires, forming a biofilm over the surface of the carbon cloth. The micrographs obtained under 12000X magnification are presented in Fig. 3(e). and Fig. 3(f). The micrographs clearly show the cross-sectional view of the carbon cloth anode with bacterial biofilm constituted of rod-shaped bacteria forming multiple layers with the prominent presence of an evenly distributed EPS layer on the carbon cloth. The bacterial biofilm was about 6.91 µm thick when implemented in BAFC-B.

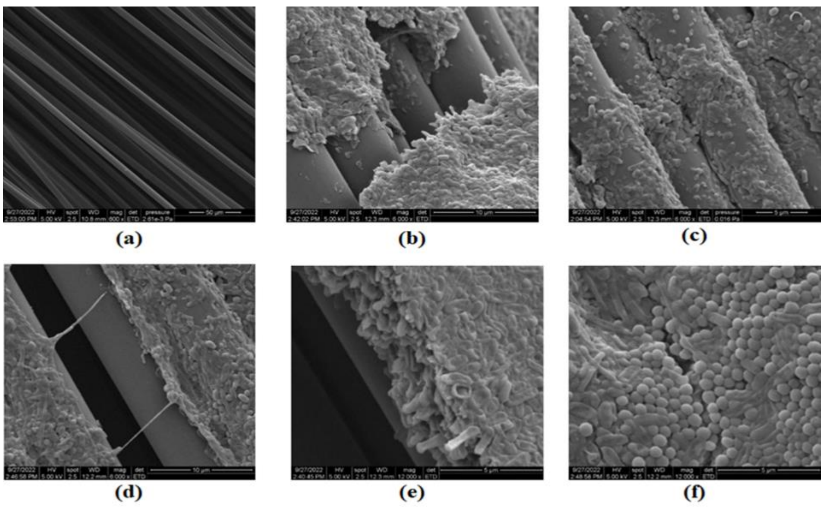


Figure 3. ESEM image of (a) carbon cloth electrode without any attached biofilm; (b) and (c) dense attachment of bacterium *Shewanella putrefaciens* MTCC 8104*;* (d) nano-wire formed by used *Shewanella putrefaciens* MTCC 8104; (e) cross sectional view of bacterial biofilm attached with the electrode surface (f) agglomerated bacterial cells of *Shewanella putrefaciens* MTCC 8104.

The compound microscopic analysis for study of dynamics of algal biofilm formation, as depicted in Figures 4 (a), (b), and (c), reveal that there is almost no attachment as observed on day 1, which has been shown in Fig. 4(a). Very little attachment of algal biomass starts to occur after day 2. On the 4th day of the study, considerable attachment of algal biofilm starts to appear on the carbon cloth surface in the form of filamentous growth, as shown in Fig. 4(b). The attachment grew denser within the following 3 days, and a thick as well as evenly distributed green layer of algal biofilm was observed on day 7, which has been shown in Fig. 4(c).

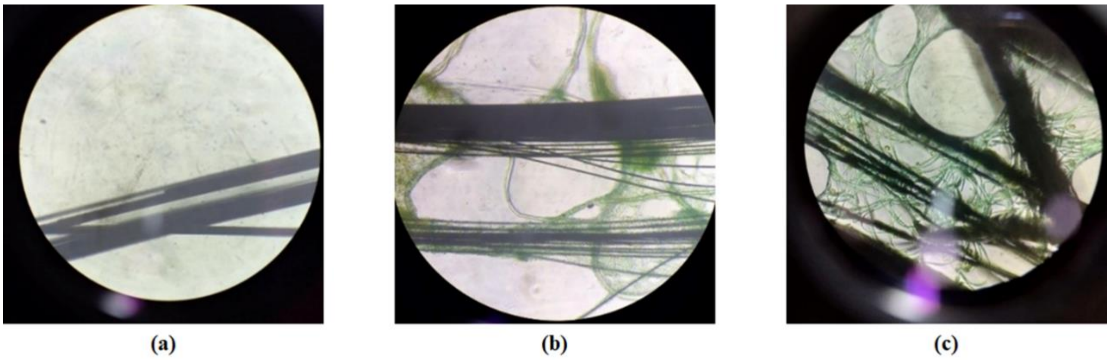


Figure 4. Compound microscopic images of (a) carbon cloth electrode without any attached biofilm; (b) distinct monolayer visible on carbon cloth surface and (c) thick multi-layered biofilm of bacterium *Leptolyngbya subtilis* JUCHE1.

The algal biofilm formed by the algal strain LS over the cathode surface was also observed under ESEM, and the micrographs have been depicted in Figures 5(a), (b), and (c). Under 150X magnification, a layer of algal biofilm is evident, as shown in Fig. 5(a). The ESEM image of the cathode with algal biofilm under 501X magnification, as shown in Fig. 5(b), clearly indicates a dense attachment of interweaved mesh-like algal biofilm on the surface of the electrode. On further magnification, a filamentous structure of algal growth becomes distinctly visible in Fig. 5(c).

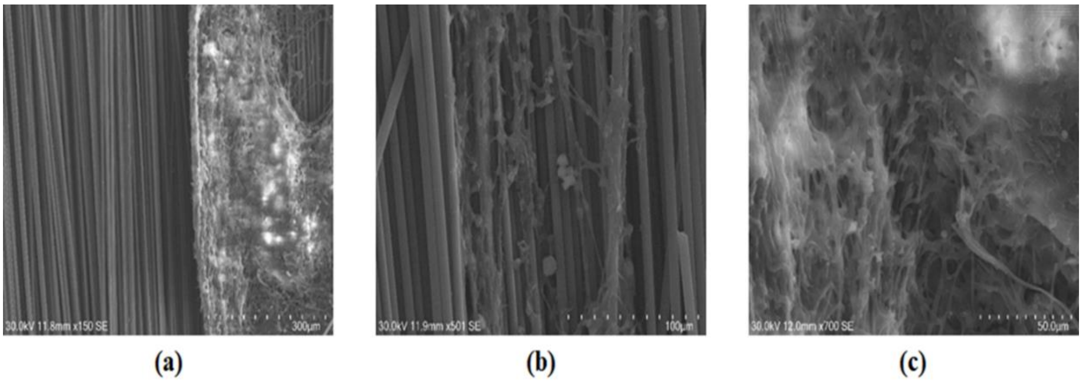
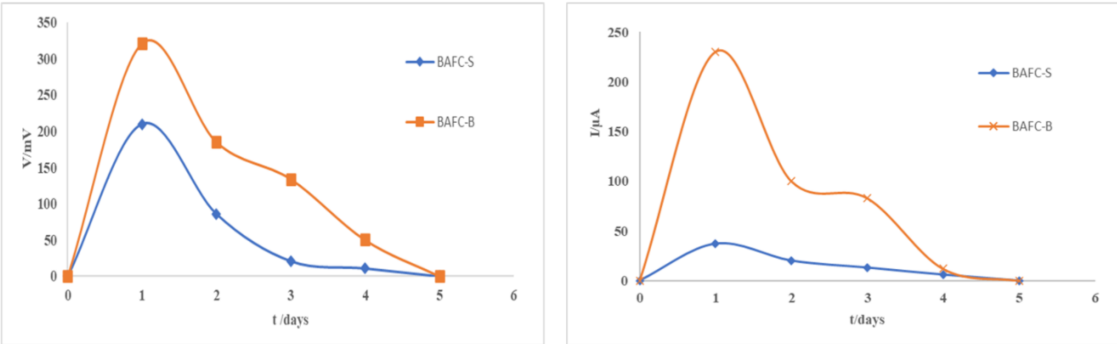


Figure 5. ESEM images showing (a) attachment to carbon cloth, (b) dense growth and (c) biofilm layer on carbon cloth formed by the algal cells of *Leptolyngbya subtilis* JUCHE1.

3.2 Electrical analysis of the DC-BAFCs

In Figures 6 (a) and 6 (b), the output voltage and current of both the BAFCs have been presented over an operating period of 5 days. In the case of BAFC-S, where both the bacterial and algal strains were in suspended form, the voltage has steadily increased initially, peaking on the very first day of operation. The average operating voltage observed was 82 mV, with an average operating current of 19 µA. This pattern can be explained by the fact that as time progresses, the release of electrons, and thus the transfer of electrons to the anode, decreases. Since the BAFCs were operated in batch mode, a falling trend after the 1st day was observed, and the output is negligible by the 5th day due to the depletion of carbon sources in the anode chamber.

In case of BAFC-B, biofilms of respective organisms were incorporated in both electrodes. The average operating voltage (172.5 mV) and current (106.25 µA) were higher than the suspended one. However, the trend followed was similar to BAFC-S, and the negligeable voltage or current conditions were reached on the 5th day. The average operating voltage, of BAFC-B (172.5 mV) are higher by 110.36%, compared to BAFC-S (82 mV). Thus, the application of biofilms of both bacteria and algae to the system showed a positive effect on the electrical performance of the DC-BAFC system. The peak current for BAFC-S was 37µA while for BAFC-B it was 230 µA. The falling trend of voltage with bacterial biofilm can be mitigated by intermittent feeding of carbon substrates and hence fed-batch operation rather than batch operation of BAFCs. Dai et al., (2020) showed that the maximum operating voltage of 364 mV was obtained when the MFC was fed with bamboo fermentation effluent rich in acetate and lactate. It was also shown that lactate was preferred over acetate as a substrate because acetate exhibits inhibitory action at higher concentrations, whereas lactate is converted to acetate during its metabolism, and Shewanella sp. fails to break down acetate further under anoxic conditions.



(a) (b)

Figure 6. Plot for (a) voltages and (b) current on corresponding days of both the BAFCs.

3.3 Electrochemical Analysis:

The BAFC was prepared following the methodology mentioned in section 2 for cyclic voltammetry (CV) analysis and the specifications related to the analysis are as follows:

Table 2:
The value of various parameters set for Cyclic Voltammetry analysis.

Parameters	Value
Full Cell	
Scan rate	25mV/s
Minimum voltage	-1V
Maximum Voltage	1 V
Start Voltage	-1V
End voltage	-1V
Cycles	1
Current limit	100 mA
Half Cell	
Scan rate	25mV/s
Minimum voltage	-2V
Maximum Voltage	3 V
Start Voltage	-2V
End voltage	-2V
Cycles	-2V
Current limit	10 mA

Table 3:
Electrodes used, their type and placement in the system.

Electrode type	Name of electrode used	Placement in BAFC
Working electrode	Carbon cloth anode	Anode Compartment
Counter electrode	Carbon cloth cathode	Cathode Compartment
Reference electrode	Saturated calomel electrode (SCE)	Cathode and Anode Compartment

Cyclic Voltammetry gives us the information about the electron transfer related reaction kinetics. It can be used to study the electron transfer efficiency of electroactive biofilms and electrodes. The current is continuously scanned as a function of changing potential. In the anode chamber, oxidation of the substrate occurs, and this oxidation and reduction are evident from cyclic voltammetry curves. The sweep potential of Fig 7a and 7b were 25 mV/s. The corresponding peak currents and peak voltages for the electron donors and the electron acceptor have been displayed in the table, thus depicting the presence of strong redox couples.

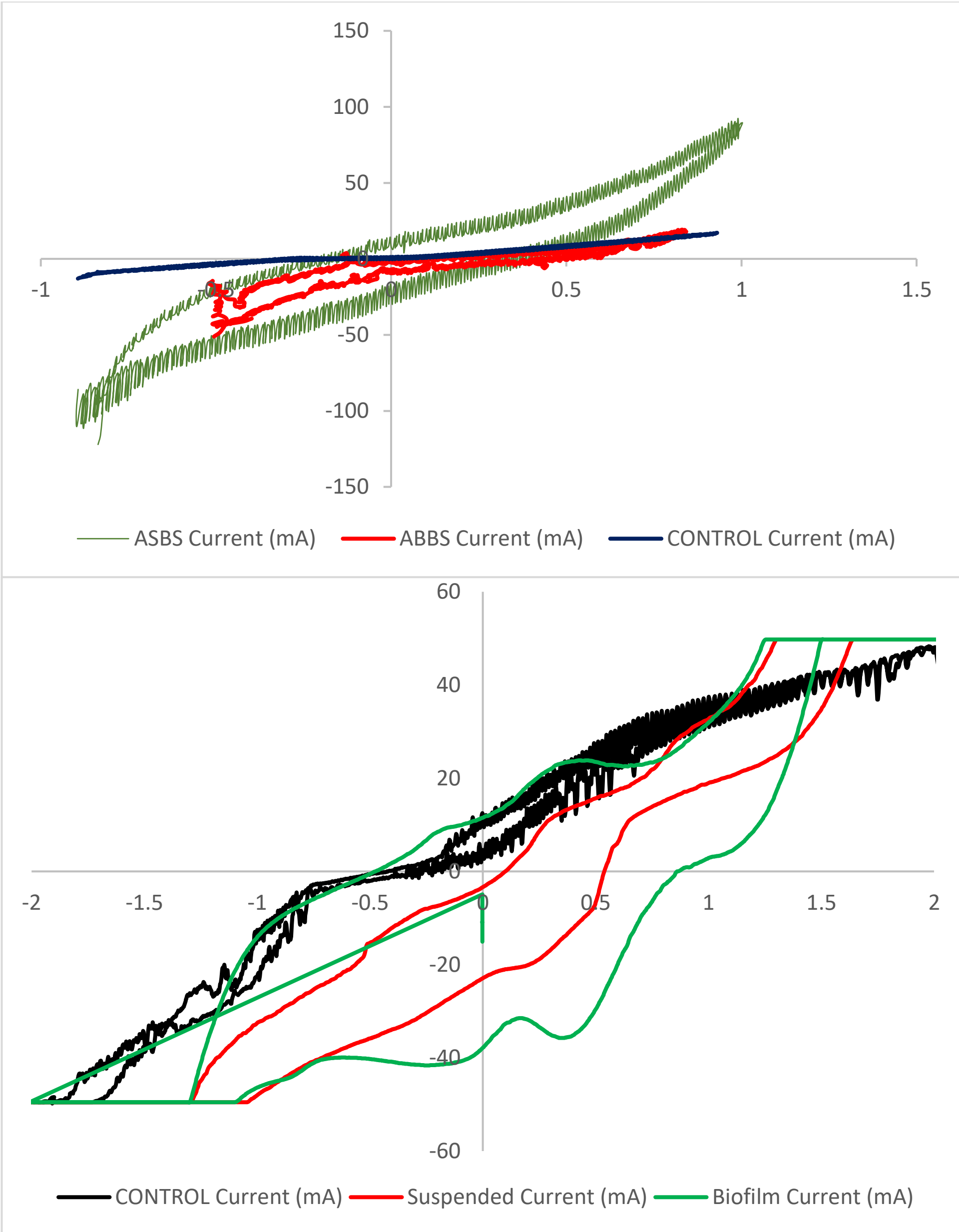


Figure 7. Cyclic voltammogram showing current for the corresponding voltages.

Table 4:
The peak voltages and peak currents obtained from the cyclic voltammogram as a result of the electrochemical reactions occurring in the system.

For BAFC I		
Substrate	**Voltage(V)**	**Current (mA)**
Lactic acid	0.5425	0.028
Oxygen	-0.5592	-0.0511
For BAFC IV		
Substrate	**Voltage(V)**	**Current (mA)**
Lactic acid	0.771	0.0741
Oxygen	-0.5514	-0.0387

It is evident from the cyclic voltammograms of BAFCs that biofilm enhanced the performance of the system along with enhanced oxidation-reduction reactions. For the systems with bacterial biofilm and algal the oxidation peak was obtained at 0.771 V which was much higher than the system with suspended bacteria and the control system. On the other hand, the reduction peak was observed at -0.5514V. Wang et al., (2024) reported an oxidation peak at 0.495 V using SP biofilm which was comparatively lower than our system.

3.4 Energy analysis based on Coulombic efficiencies

The Coulombic efficiency for BAFC-B with both bacterial and algal biofilm was 33.06%, which was the higher than BAFC-S under study (Li et al., 2023; Cao et al., 2021). For BAFC-S, it was 5.91%, the lowest one, which is almost at par with the one obtained in an earlier report where they fed 20 mM lactate as carbon source to *Shewanella oneidensis* (Li et al., 2018). Thus, it can stated that the use of biofilms in anode as well as cathode has a positive effect on the performance of the BAFCs.

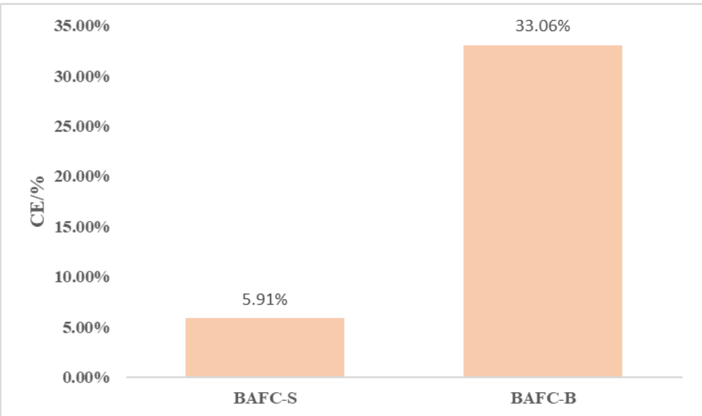


Figure 8. Energy analysis data for the four systems based on CE

3.5 Environmental analysis based on ACE

The analysis was done to check the carbon emission by our systems (Mittal et al., 2012), but since algae was present in the cathode chamber, for BAFCs, CO_2 emission is negative because the algal culture in the cathode captures or assimilates the emitted CO_2, which is why it is higher than 100% for all of our systems. The power generated in watts (on a daily basis) for both the systems under study are 0.007 mW (BAFC-S) and 0.074 mW (BAFC-B), respectively. For BAFC-S, the ACE value was 627.75%, which was much higher as compared to BAFC-B it was 201.75%. Unlike the trend followed by the coulombic efficiency of the systems, the ACE values showed an exactly opposite trend. The assimilation of CO_2 was higher in the case of DC-BAFCs with either suspended algae or bacteria as compared to DC-BAFCs that had biofilm in it because the CO_2 generated in the anode chamber was evenly dissolved throughout the catholyte medium, which was easily accessible to the evenly distributed suspended algal biomass as compared to the algal biofilm. Again, on the other hand, when the bacteria were freely suspended in the anolyte medium, they could oxidize the substrate entirely, though the conduction of electrons was low.

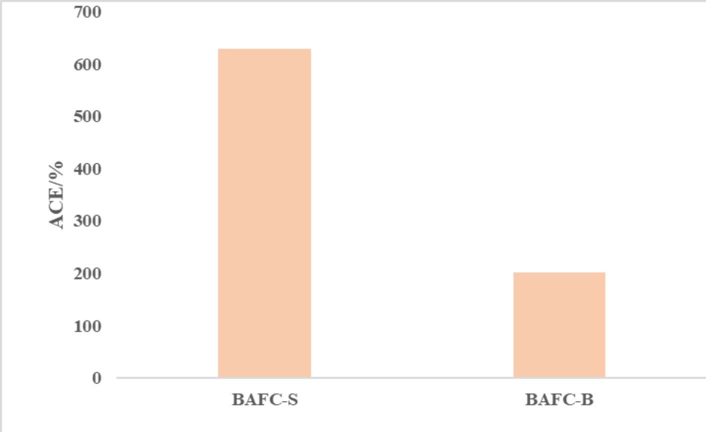


Figure 9. Data on ACE for the four systems.

4. Conclusion

The present study demonstrated a dual-chambered BAFC incorporating electroactive bacteria in the anode chamber which plays a crucial role in effecting the electrical efficiency of the system; thus, application of the organisms in the form of biofilm can enhance the efficiency of the system manifold. It has been observed that the application of bacterial biofilm can enhance the performance of the system by improving the electron transport after substrate breakdown directly from the biofilm to the anode surface, alongside diminishing the loss of electrons that is observed in the case of suspended bacterial culture; thus, enhancing the stability of the overall system which is evident from the coulombic efficiencies of the systems. On the other hand, the algal biofilm also improves the oxygen reduction reaction by accepting the transported electrons via cathode along with the assimilation of the carbon dioxide generated by the anode reaction. On the other hand, use of cyanobacterial strain as biocathode explored a lesser studied area of fuel cell studies. Hence, application of biofilms showed promising results concerning the bio-electricity generation by direct electron transfer as well as making the system cost effective by alleviating the need for replenishment of synthetic electron acceptors and replacing the expensive proton exchange membrane; moreover, the algal biomass generated in the cathode chamber can be further processed for obtaining valuable bioproducts.

Statements and Declaration

Authors contributions

The overall research study was supervised by Prof. Ranjana Chowdhury. Ms Sudipta Ghosh was involved in Experimental Studies related to all the BAFCs under the study using both suspended and biofilm and the theoretical analyses under the guidance of Prof. Ranjana Chowdhury. Mrs Snigdha Mandal was involved in the development of BAFCs using suspended microorganisms under the study. Voltametric studies were conducted by both Mrs Snigdha Mandal and Ms Sudipta Ghosh under the guidance of Prof. Ranjana Chowdhury. The manuscript was written by Ms Sudipta Ghosh under the guidance of Prof. Ranjana Chowdhury.

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Availability of Data and Materials

Additional data are available in the supplementary section and will be made available on request.

Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

Research involving human participants and/or animals

This article does not contain any studies with human participants or animals performed by the authors.

Informed consent

Consent to Publish

Not applicable

Consent to Participate

Not applicable

References

Aiyer, Kartik S. “Synergistic Effects in a Microbial Fuel Cell between Co-Cultures and a Photosynthetic Alga Chlorella Vulgaris Improve Performance.” *Heliyon*, vol. 7, no. 1, Jan. 2021, p. e05935. *DOI.org*

(Crossref), https://doi.org/10.1016/j.heliyon.2021.e05935.
Antolini, Ermete. "Composite Materials for Polymer Electrolyte Membrane Microbial Fuel Cells." Biosensors and Bioelectronics, vol. 69, July 2015, pp. 54–70. DOI.org (Crossref), https://doi.org/10.1016/j.bios.2015.02.013.
Barana, A. C., et al. "Development of a fermented dairy beverage using cheese quark sour whey." *Revista Verde de Agroecologia e DesenvolvimentoSustentável* 7.5 (2012).
Cao, Bocheng, Zipeng Zhao, Lele Peng, Hui-Ying Shiu, Mengning Ding, Frank Song, Xun Guan, et al. "Silver Nanoparticles Boost Charge-Extraction Efficiency in *Shewanella* Microbial Fuel Cells." *Science* 373, no. 6561 (September 17, 2021): 1336–40. https://doi.org/10.1126/science.abf3427.
Chaudhary, Vandana, et al. "Valorization of Dairy Wastes into Wonder Products by the Novel Use of Microbial Cell Factories." Trends in Food Science & Technology, vol. 142, Dec. 2023, p. 104221. DOI.org (Crossref), https://doi.org/10.1016/j.tifs.2023.104221.
Dai, Hue Ngan, et al. "Power Generation of Shewanella Oneidensis MR-1 Microbial Fuel Cells in Bamboo Fermentation Effluent." International Journal of Hydrogen Energy, vol. 46, no. 31, May 2021, pp. 16612–21. DOI.org (Crossref), https://doi.org/10.1016/j.ijhydene.2020.09.264.
Das, Sumona, et al. "Studies on Power Plant Algae: Assessment of Growth Kinetics and Bio-Char Production from Slow Pyrolysis Process." Indian Chemical Engineer, vol. 63, no. 2, Mar. 2021, pp. 129–38. DOI.org (Crossref), https://doi.org/10.1080/00194506.2020.1845987.
Drapcho C, Nghiem J, Walker T (2008) Biofuels Engineering Process Technology. McGraw-Hill Co., New York
Elgrishi, Noémie, et al. "A Practical Beginner's Guide to Cyclic Voltammetry." *Journal of Chemical Education*, vol. 95, no. 2, Feb. 2018, pp. 197–206. *DOI.org (Crossref)*, https://doi.org/10.1021/acs.jchemed.7b00361.
Fang, Zhou, et al. "Electricity Production from Azo Dye Wastewater Using a Microbial Fuel Cell Coupled Constructed Wetland Operating under Different Operating Conditions." Biosensors and Bioelectronics, vol. 68, June 2015, pp. 135–41. DOI.org (Crossref), https://doi.org/10.1016/j.bios.2014.12.047
Gadhamshetty, Venkataramana, et al. "Evaluation of Laminaria-Based Microbial Fuel Cells (LbMs) for Electricity Production." Bioresource Technology, vol. 127, Jan. 2013, pp. 378–85. DOI.org (Crossref), https://doi.org/10.1016/j.biortech.2012.09.079.
Gajda, Iwona, et al. "Self-Sustainable Electricity Production from Algae Grown in a Microbial Fuel Cell System." *Biomass and Bioenergy*, vol. 82, Nov. 2015, pp. 87–93. *DOI.org (Crossref)*, https://doi.org/10.1016/j.biombioe.2015.05.017.
Kant Bhatia, Shashi, et al. "Advances in Algal Biomass Pretreatment and Its Valorisation into Biochemical and Bioenergy by the Microbial Processes." Bioresource Technology, vol. 358, Aug. 2022, p. 127437. DOI.org (Crossref), https://doi.org/10.1016/j.biortech.2022.127437.
Khandelwal, Amitap, Ankisha Vijay, Ambesh Dixit, and Meenu Chhabra. "Microbial Fuel Cell Powered by Lipid Extracted Algae: A Promising System for Algal Lipids and Power Generation." Bioresource Technology 247 (January 2018): 520–27. https://doi.org/10.1016/j.biortech.2017.09.119.
Kim, Hyung Joo, et al. "A Mediator-Less Microbial Fuel Cell Using a Metal Reducing Bacterium, *Shewanella Putrefaciens*." Enzyme and Microbial Technology, vol. 30, no. 2, Feb. 2002, pp. 145–52. DOI.org (Crossref), https://doi.org/10.1016/S0141-0229(01)00478-1.
Kokabian, Bahareh, and Veera Gnaneswar Gude. "Photosynthetic Microbial Desalination Cells (PMDCs) for Clean Energy, Water and Biomass Production." Environmental Science: Processes & Impacts, vol. 15, no. 12, 2013, p. 2178. DOI.org (Crossref), https://doi.org/10.1039/c3em00415e.
Liu, Ting, et al. "Bioelectricity Generation in a Microbial Fuel Cell with a Self-Sustainable Photocathode." The Scientific World Journal, vol. 2015, 2015, pp. 1–8. DOI.org (Crossref), https://doi.org/10.1155/2015/864568.
Li, Feng, Yuan-Xiu Li, Ying-Xiu Cao, Lei Wang, Chen-Guang Liu, Liang Shi, and Hao Song. "Modular Engineering to Increase Intracellular NAD(H/+) Promotes Rate of Extracellular Electron Transfer of Shewanella Oneidensis." Nature Communications 9, no. 1 (September 7, 2018): 3637. https://doi.org/10.1038/s41467-018-05995-8.
Li, Feng, Rui Tang, Baocai Zhang, Chunxiao Qiao, Huan Yu, Qijing Liu, Junqi Zhang, Liang Shi, and Hao Song. "Systematic Full-Cycle Engineering Microbial Biofilms to Boost Electricity Production in *Shewanella Oneidensis*." *Research* 6 (January 2023): 0081. https://doi.org/10.34133/research.0081.
Logroño, Washington, et al. "Single Chamber Microbial Fuel Cell (SCMFC) with a Cathodic Microalgal Biofilm: A Preliminary Assessment of the Generation of Bioelectricity and Biodegradation of Real Dye Textile Wastewater." Chemosphere, vol. 176, June 2017, pp. 378–88. DOI.org (Crossref), https://doi.org/10.1016/j.chemosphere.2017.02.099
Mahmoud, Rehab H., et al. "Waste to Energy Conversion Utilizing Nanostructured Algal-based Microbial Fuel Cells." Electrochemical Science Advances, vol. 2, no. 6, Dec. 2022, p. e2100071. DOI.org (Crossref), https://doi.org/10.1002/elsa.202100071.

Marassi, Rodrigo José, et al. “Efficient Dairy Wastewater Treatment and Power Production Using Graphite Cylinders Electrodes as a Biofilter in Microbial Fuel Cell.” Biochemical Engineering Journal, vol. 178, Jan. 2022, p. 108283. DOI.org (Crossref), https://doi.org/10.1016/j.bej.2021.108283.

Mittal ML, Sharma Cand Singh R (2012). Estimates of emissions from coal fired thermal power plants in India. In 2012 Int. emission inventory conf (pp. 13-16).

Mukherjee, Anwesha, et al. “Optimization of Microbial Fuel Cell Process Using a Novel Consortium for Aromatic Hydrocarbon Bioremediation and Bioelectricity Generation.” Journal of Environmental Management, vol. 298, Nov. 2021, p. 113546. DOI.org (Crossref), https://doi.org/10.1016/j.jenvman.2021.113546.

Neethu, B., et al. “A Novel Proton Exchange Membrane Developed from Clay and Activated Carbon Derived from Coconut Shell for Application in Microbial Fuel Cell.” Biochemical Engineering Journal, vol. 148, Aug. 2019, pp. 170–77. DOI.org (Crossref), https://doi.org/10.1016/j.bej.2019.05.011.

Nishio, Koichi, et al. “Light/Electricity Conversion by Defined Cocultures of Chlamydomonas and Geobacter.” Journal of Bioscience and Bioengineering, vol. 115, no. 4, Apr. 2013, pp. 412–17. DOI.org (Crossref), https://doi.org/10.1016/j.jbiosc.2012.10.015

Panda, Jigisha, and Ranjana Chowdhury. “Growth Kinetic Study of Electrochemically Active Bacterium *Shewanella Putrefaciens* MTCC 8104 on Acidic Effluent of Jute Stick Pyrolysis.” Indian Chemical Engineer, vol. 63, no. 2, Mar. 2021, pp. 193–205. DOI.org (Crossref), https://doi.org/10.1080/00194506.2020.1803150.

Pinchuk, Grigoriy E., et al. “Pyruvate and Lactate Metabolism by Shewanella Oneidensis MR-1 under Fermentation, Oxygen Limitation, and Fumarate Respiration Conditions.” Applied and Environmental Microbiology, vol. 77, no. 23, Dec. 2011, pp. 8234–40. DOI.org (Crossref), https://doi.org/10.1128/AEM.05382-11.

Ramanaiah, S. V., et al. “Bioelectrochemical Systems (BESs) for Agro-Food Waste and Wastewater Treatment, and Sustainable Bioenergy-A Review.” Environmental Pollution, vol. 325, May 2023, p. 121432. DOI.org (Crossref), https://doi.org/10.1016/j.envpol.2023.121432.

Sarma, Pranab Jyoti, and Kaustubha Mohanty. “Development and Comprehensive Characterization of Low-Cost Hybrid Clay Based Ceramic Membrane for Power Enhancement in Plant Based Microbial Fuel Cells (PMFCs).” Materials Chemistry and Physics, vol. 296, Feb. 2023, p. 127337. DOI.org (Crossref), https://doi.org/10.1016/j.matchemphys.2023.127337.

Ucar, Deniz, et al. “An Overview of Electron Acceptors in Microbial Fuel Cells.” Frontiers in Microbiology, vol. 8, Apr. 2017. DOI.org (Crossref), https://doi.org/10.3389/fmicb.2017.00643

Vennila Lakshmanan, N. J., Kaliyamoorthi, K., Subashchandrabose, O., Raj, T. C., & Kamaraj, S. K. (2024). Insights on Algae-based Microbial Fuel Cells. Photosynthesis-Assisted Energy Generation: From Fundamentals to Lab Scale and In-Field Applications, 127-152.

Wang, Lili, Yue Zhou, Qi Min, and Youbin Si. “Vanadium (V) Reduction and the Performance of Electroactive Biofilms in Microbial Fuel Cells with Shewanella Putrefaciens.” *Journal of Environmental Management* 370 (November 2024): 122592. https://doi.org/10.1016/j.jenvman.2024.122592.

Wang, X., Hong, Y., & Zhang, Y. (2023). Photosynthetic algal microbial fuel cell (PAMFC) for wastewater removal and energy recovery: a review. Current Pollution Reports, 9(3), 359-373.

Wei, Qian, Enhanced Degradation Performance and Microbial Community Diversity Analysis of a Microbial Electrolytic Cell with a Double Chamber for the Treatment of Wastewater Containing P-Bromoaniline. Biochemical Engineering Journal, vol. 185, July 2022, p. 108539. DOI.org (Crossref), https://doi.org/10.1016/j.bej.2022.108539.

Xu, Bin, et al. “Deciphering Electron-Shuttling Characteristics of Microalgal Metabolites upon Bioelectricity-Generating Community in Microbial Fuel Cells.” Biochemical Engineering Journal, vol. 144, Apr. 2019, pp. 148–56. DOI.org (Crossref), https://doi.org/10.1016/j.bej.2019.01.018.

Yaakop, Amira Suriaty, et al. “Domestic Organic Waste: A Potential Source to Produce the Energy via a Single-Chamber Microbial Fuel Cell.” International Journal of Chemical Engineering, edited by Showkat Bhawani, vol. 2023, Apr. 2023, pp. 1–10. DOI.org (Crossref), https://doi.org/10.1155/2023/2425735.

Ye, Min, Borchen Sun, Liuying Song, Yu Qin, Jinghuan Luo, Aijun Zhu, and Yu-You Li. “Organic Transformation, Lactic Acid Metabolism, and Membrane Performance in High-Rate Methanogenic Treatment of Dairy Processing Wastewater Using Thermophilic High-Solid Anaerobic Membrane Bioreactor.” Chemical Engineering Journal 455 (January 2023): 140780. https://doi.org/10.1016/j.cej.2022.140780.

Zhang, Xiuling, et al. “Simultaneous Degradation of High Concentration of Citric Acid Coupled with Electricity Generation in Dual-Chamber Microbial Fuel Cell.” Biochemical Engineering Journal, vol. 173, Sept. 2021, p. 108095. DOI.org (Crossref), https://doi.org/10.1016/j.bej.2021.108095.

Integrating Waste Legislation and Circular Economy Strategies in Climate Policy: International Lessons and Georgia's Experience

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ABSTRACT

The transition toward a circular economy (CE) has gained momentum worldwide, supported by regulatory reforms, economic incentives, and technological innovations. Yet progress remains uneven, particularly in transition and developing economies where enforcement, infrastructure, and public engagement are limited. This review synthesizes international literature and compares selected jurisdictions using a structured set of parameters: (i) national CE policies and regulatory frameworks, (ii) Extended Producer Responsibility (EPR) and economic instruments, (iii) recycling and separate collection systems, (iv) integration with greenhouse gas (GHG) reduction targets, (v) enforcement capacity, and (vi) public participation. The analysis shows that advanced economies such as Austria, South Korea, and Japan achieve higher recycling rates and measurable climate benefits through integrated policy mixes that combine legislation, financial incentives, and citizen engagement. In contrast, fragmented approaches in the United States, Canada, and Australia deliver uneven results, while transition economies—including Georgia—remain at early stages of CE implementation. Georgia has introduced the Waste Management Code (2014), Vision 2030, and a National Waste Management Strategy, but continues to face barriers of weak enforcement, limited infrastructure, and low circularity (≈1.3%). The review highlights that Georgia's progress will depend on embedding existing legislation into a coherent policy mix, investing in infrastructure and enforcement, strengthening public-private partnerships, and aligning CE more closely with climate objectives. These findings provide insights for policymakers in Georgia and other middle-income countries on how international best practices can guide effective CE transitions and contribute to climate change mitigation.

Keywords: Extended Producer Responsibility (EPR); Policy mixes; Regulatory instruments; Material recovery rates.

AI Disclosure: Minimal use of AI Assistance for Language and Style: The author acknowledges the use of AI-based tools for minor language editing or grammatical correction. However, all intellectual contributions, analyses, and conclusions presented in these manuscripts are entirely the author's own.

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1. Introduction

Circular Economy (CE) is a cyclical, regenerative system that minimises resource inputs, waste, emissions, and energy. Effective management of waste and the adoption of circular economy principles have emerged as pivotal elements within global strategies to address climate change and advance sustainable development. Waste generation and its inadequate management not only strain ecosystems but also contribute significantly to greenhouse gas (GHG) emissions, particularly methane, while depleting materials that could otherwise be reused in production cycles (Bogner et al., 2008; IPCC, 2021). Against this backdrop, integrated waste legislation and circular economy (CE) strategies are increasingly recognized as crucial policy instruments. They offer a way to mitigate climate impacts, preserve natural resources, and build more resilient and efficient economies (European Commission, 2020; Schröder et al., 2020). Moving beyond the traditional "take-make-dispose" approach, the circular model emphasizes prevention, reuse, recycling, and recovery, thereby minimizing both waste and emissions (Ellen MacArthur Foundation, 2019; Ghosh & Ghosh , 2021, Ghosh, S. K., 2020).

In Georgia, the urgency of this transition is particularly evident. Rapid urbanization and steadily rising volumes of municipal solid waste (MSW) put mounting pressure on limited infrastructure and institutional capacity (World Bank, 2018). At the same time, these challenges create a window of opportunity: by embedding CE principles into waste management policy, Georgia can both modernize its environmental governance and advance its climate goals. Some important steps have already been taken, especially through the harmonization of national legislation with the European Union (EU) framework under the Association Agreement. The Waste Management Code of Georgia (2015) and the introduction of Extended Producer Responsibility (EPR) schemes represent important milestones (Parliament of Georgia, 2015; Ministry of Environmental Protection, 2016). Yet, significant gaps remain in enforcement, infrastructure development, monitoring mechanisms, and public engagement (UNEP, 2019). Without addressing these weaknesses, the transformative potential of CE remains only partially realized.

The climate dimension adds another layer of urgency. Waste sector emissions—especially from landfills - remain a major source of methane, while inefficient resource use heightens the country's vulnerability to energy and material insecurity (NDC of Georgia, 2021). Integrating CE strategies into climate mitigation policies offers Georgia a unique opportunity to link waste management reform directly to its Nationally Determined Contributions (NDCs) under the Paris Agreement (Government of Georgia, 2021). In this way, the country can not only achieve measurable reductions in greenhouse gas emissions but also foster new pathways for sustainable economic development, enhance resource efficiency, and strengthen long-term socio-economic resilience (D'Amato et al., 2020).

The objective of this paper is to analyse the governance instruments and implementation challenges of circular-economy relevant waste legislation and to extract lessons for Georgia's climate-aligned waste policy. To do so, we conduct a systematic literature review and synthesise evidence on policy mixes and CE governance, present a targeted comparative policy overview of selected jurisdictions to highlight different instruments and implementation experiences, and provide an illustrative national case-study of Georgia that summarises current legislation, key achievements, infrastructure and enforcement gaps, and realistic opportunities for policy transfer. The paper closes with conclusions and prioritized recommendations for Georgia.

2. Methods and Materials

The study employed a qualitative, comparative case study design to evaluate CE policies and their relevance to climate mitigation. The following methods were applied:

– ***Systematic Literature Review.*** Academic publications, policy reports, and institutional documents published between 2015 and 2024 were reviewed. Search databases included Scopus, Web of Science, and Google Scholar, using keywords such as *CE*, *waste governance*, *extended producer responsibility*, and *climate policy*;

– ***Country selection and scope.*** The countries selected for the comparative overview were chosen purposively to represent: (i) a range of CE policy maturity (advanced EU members and early-stage transition economies), (ii) geographic diversity and policy innovation (EU, North America, East Asia, Australia), (iii) relevance to Georgia (EU as a normative anchor through the Association Agreement and Russia as a neighbouring large economy), and (iv) availability of official policy documents and peer-reviewed analyses. The study is therefore **illustrative** (targeted comparative overview), not exhaustive; this is explicitly stated to avoid implying quantitative cross-country statistical analysis.

3. Literature Review

The literature on CE and waste management has expanded significantly in recent years, reflecting both conceptual advances and policy experimentation worldwide. Several key themes emerge: digital innovation, regulatory frameworks, socio-economic integration, and regional challenges.

CE aims to stop waste from being produced in the first place, and replace the dominant "take-make-dispose" economic system with one that is resource efficient and regenerative by keeping resources in continuous use at their highest possible value. By making changes across the entire material life cycle (LC), CE can support us in achieving sustainable consumption and production (Building Canberra's Circular Economy, 2023; Ghosh & Ghosh, 2021). Waste generation has become one of the defining challenges of the 21st century, with global Municipal Solid Waste (MSW) expected to rise from 2.24 billion tonnes in 2020 to 3.88 billion tonnes by 2050 (World Bank, 2018). Waste management is not only an environmental issue but also a critical climate policy concern: the sector contributes to greenhouse gas (GHG) emissions through landfilling, open burning, and inefficient recycling practices (IPCC, 2022). Integrated waste legislation aligned with CE principles is increasingly recognized as a strategic pathway to mitigate climate change, conserve resources, and foster sustainable growth (Kirchherr, 2017; Elizbarashvili et al., 2002; Elizbarashvili et al., 2018).

The CE represents a vital step in the search for proper balance between economic growth and environmental sustainability. A growing body of literature reviews highlights the theoretical foundations of CE, the policy instruments deployed to support it, and their relative effectiveness. For example, within European Union (EU), the policy framework encompasses more than 100 distinct measures, all of which explicitly address different stages of the product life cycle (Hartley, K., 2023). The circular model has been tested across micro-level contexts (individual firms), meso-level systems (eco-industrial parks), and macro-level strategies (national governments) (Mhatre et al, 2021).

The 3R framework (reduce, reuse, recycle) within CE paradigms is gaining traction as a mitigation tool; yet research indicates that standalone policies (e.g., bans) are ineffective without incentives or fiscal tools. Advanced jurisdictions are legislating strategic mixes.

Against this background, the present study examines structural and practical dimensions of policy frameworks in the different countries of the world, including Georgia. It not only provides a systematic review of relevant literature but also contextualizes regulatory and fiscal instruments while assessing their effectiveness in terms of climate change mitigation.

The central argument advanced here is that the effectiveness of 3R principles and broader CE strategies increases substantially when they are implemented as part of a comprehensive policy mix that combines regulatory and fiscal measures. For Georgia, this implies the need to build upon digital, institutional, and infrastructural capacities as a foundation for advancing its CE transition.

Recent scholarship continues to refine the conceptual underpinnings of the circular economy (CE). Current research is clarifying and expanding the fundamental ideas, definitions, and theories that shape CE. Rather than equating it solely with recycling, recent frameworks emphasize the systemic slowing, narrowing, and closing of resource loops through product design, repair, reuse, and waste prevention (Chennak et al., 2024; Ghosh & Ghosh, 2023; Zocco & Malvezzi, 2024; Moalem, R. M., & Ghosh, S. K. (2024). These approaches position CE as a comprehensive socio-technical transition that integrates economic, environmental, and social objectives while embedding waste strategies within broader climate mitigation agendas (European Commission, 2020; Yang et al., 2023).

The effectiveness of CE depends on integrated policy mixes. Comparative analyses show that regulatory tools such as Extended Producer Responsibility (EPR), landfill bans, and eco-design standards are most effective when combined with economic incentives like deposit-refund systems or pay-as-you-throw schemes. Recent evidence suggests that fragmented or stand-alone bans often underperform, while coherent mixes improve both waste diversion rates and material recovery (OECD, 2022; Gupta, & Sahay, 2015; Rahmani et al., 2020; DiSilvio et al., 2023; European Environment Agency, 2023; World Bank, 2020). France's Anti-Waste and Circular Economy Law, for example, illustrates how multi-level regulatory measures can accelerate systemic change by coupling bans with repairability indices and eco-modulation of fees (France's Ministry, 2022).

A notable trend in the literature since 2022 is the rise of digital product passports (DPPs) and data-driven monitoring systems. These tools enable traceability of materials across value chains and facilitate reuse, repair, and recycling decisions (Abid et al., 2024). Smart tags and IoT technologies are now tested in electronics, textiles, and construction sectors, providing real-time data on product composition and condition (Hakola et al., 2025).

However, unresolved challenges remain regarding interoperability, governance, and data protection (Ducuing, & Reich, 2023).

Research increasingly addresses the social aspects of CE, particularly the role of informal workers and local communities. Case studies from Latin America and South Asia show that waste pickers play a vital role in material recovery, but lack adequate recognition, income security, and occupational safety (Wilson et al., 2006). Inclusive CE models demonstrate that integrating informal sectors through cooperatives or hybrid EPR schemes can improve both efficiency and equity (Schröder, 2020). In addition, the potential of CE for job creation in repair and remanufacturing is well-documented, though outcomes are highly context-dependent (ILO, 2023).

For transition economies like Georgia, the literature identifies structural constraints, including limited infrastructure, weak enforcement capacity, and insufficient fiscal instruments (OECD, 2023). Experiences from Central and Eastern Europe suggest that gradual implementation - starting with baseline waste data, pilot projects for separate collection, and phased EPR introduction can support CE adoption (Velenturf, & Purnell, 2021). At the same time, alignment with international frameworks (e.g., EU CE Action Plan) provides both opportunities and obligations for harmonization (European Commission, 2020).

Despite rapid progress, gaps remain in the empirical evaluation of CE policies (Ghosh & Ghosh, 2021). Scholars call for longitudinal studies on policy mixes, standardized indicators linking CE to climate change mitigation, and deeper analysis of digital infrastructures for circularity (Wenting et al., 2022). Furthermore, little is known about the socio-economic impacts of CE in small and middle-income countries, particularly regarding labor markets and informal sectors (Schröder & Barrie, 2024; OECD, 2023; UNIDO, 2025; PWC, 2025).

The global transition toward a circular economy (CE) is accelerating, supported by regulatory reforms, economic incentives, and technological innovations. Nevertheless, significant challenges remain regarding the scalability of CE frameworks, their social inclusiveness, and their effectiveness in achieving long-term climate mitigation. In high-income countries, comprehensive policy packages and enforcement mechanisms are being strengthened, yet evidence from transition and developing economies is limited. Key uncertainties concern the institutional capacity to implement and enforce CE legislation, the extent to which policies address equity and stakeholder participation, and the readiness to adopt digital technologies for monitoring and traceability. Moreover, most existing studies concentrate on individual policy instruments or short-term outcomes, while fewer investigate long-term impacts on greenhouse gas reduction and systemic sustainability transitions. This research gap is particularly evident in small and middle-income countries such as Georgia, where circular economy initiatives are at an early stage of development and face constraints in infrastructure, enforcement, and public engagement.

4. Results and Discussion

International experiences reveal that circular economy (CE) implementation follows diverse national pathways, yet several common parameters allow for structured comparison. These include: (i) the presence of national CE policies and regulatory frameworks (European Commission, 2020; Hartley et al., 2023), (ii) the use of Extended Producer Responsibility (EPR) and economic instruments (Gupta & Sahay, 2015; OECD, 2022), (iii) the scale and effectiveness of separate collection and recycling systems (European Environment Agency, 2023; Wilson et al., 2006), (iv) the integration of CE with greenhouse gas (GHG) reduction objectives (Bogner et al., 2008; Ellen MacArthur Foundation, 2019), (v) institutional enforcement capacity (Kirchherr et al., 2018), and (vi) levels of public engagement (Schröder, 2020). Using these yardsticks provides a consolidated and consistent basis for comparison, moving beyond descriptive case summaries toward systematic evaluation. **Table 1** synthesizes these parameters across selected countries and Georgia, highlighting both the diversity of national approaches and areas of consolidation, while offering a benchmark to identify Georgia's progress, gaps, and opportunities.

Table 1. Summary of key CE and waste-management factors in selected countries and Georgia

Country/Region	CE / EPR Laws	Separate Collection	Recycling / Circularity	EPR & Incentives	Enforcement & Engagement
USA	No single CE law; state-led	Variable	>50% landfilled; recycling ~32%	Patchwork EPR & deposits	Fragmented enforcement; uneven awareness
Canada	Federal framework; strong provincial EPR	Strong in leading provinces	High in EPR provinces	Widespread provincial EPR	Strong provincial agencies; engagement efforts
Russia	Federal waste law; CE nascent	Low	Recycling ~7–8%	Nascent EPR	Weak enforcement, low awareness
China	CE Promotion Law; bans & EPR	Rapid expansion	CMU ~23%	Robust EPR & bans	Strengthened enforcement; growing awareness
S. Korea	Comprehensive CE & EPR framework	Mandatory separation (esp. food waste)	Food waste recycling >95%	EPR + PAYT	Strong enforcement; high public awareness
Japan	CE Basic Act + sectoral laws	Extensive separation	MSW ~20%; strong industrial recovery	Product-specific EPR	Strong institutions & culture
EU	CE Action Plan; binding targets	Mandated, varies by MS	CMU avg. ~11.5%	Widespread EPR & deposits	Oversight + public campaigns
Austria	National CE strategy; EU-aligned	High-quality; minimal landfill	Recycling ~63%; CMU ~15.4%	Strong EPR, modulated fees	High enforcement; strong participation
Australia	State-level CE strategies	Uneven	Recovery improving	Expanding EPR & PAYT pilots	Mixed enforcement; engagement variable
India	EPR regulations under plastic, e-waste and battery rules	Limited, urban pilots	Recycling ~30–60% in some sectors; circularity is limited	Mandatory EPR targets and certificates; PROs active	CPCB and state boards enforce; awareness uneven
Turkey	No single CE law; waste framework aligned with EU directives	Municipal separate collection expanding	Recycling ~25–30%; landfill still dominant	Deposit-return scheme for plastics planned; EPR for packaging	Ministry of Environment oversees; EU accession drives engagement
Georgia	Waste Code (2014), early EPR	Limited, urban-focused	Recycling & CMU ~1.3%	Weak EPR coverage	Enforcement gaps; low awareness

As shown in Table 1, advanced economies such as Austria, Japan, and South Korea demonstrate integrated frameworks that combine legislation, economic instruments, and citizen engagement, resulting in high recycling rates and measurable contributions to climate goals. When consolidated along these parameters, these countries show the strongest integration of CE principles, combining binding legislation with well-developed Extended Producer Responsibility (EPR) schemes, fiscal tools such as pay-as-you-throw or deposit-refund systems, and high levels of citizen participation (Waste Management World, 2023; MESK, 2018; Sound Material-Cycle Society Indicators, 2022). These mixes have translated into tangible outcomes: Austria achieves over 60% recycling rates (FTI, 2022), South Korea recycles more than 95% of food waste (OECD, 2021), and Japan has developed strong industrial recycling chains (Basic Act for Establishing a Sound Material-Cycle Society, 2000). Importantly, in these jurisdictions, CE strategies are closely linked to climate policy, explicitly contributing to greenhouse gas (GHG) reduction targets (IPCC, 2022; Yang et al., 2023). By contrast, Georgia and other transition economies remain at early stages, with limited infrastructure, weak enforcement, and low circularity, despite having adopted initial legal frameworks (Florin et al., 2025).

In India, the implementation of extended producer responsibility (EPR) in plastic, e-waste, and battery management regulations has been recognized as a key driver of sustainable development practices, although challenges remain in bridging the gap between the formal and informal waste management sector (Gupta & Dash, 2023). s. In Turkey, municipal solid waste management policies are increasingly aligned with the EU's circular economy principles, but recycling rates remain relatively low and landfilling remains the dominant practice (Gokkurt Baki & Ergun, 2021). .

Austria's approach is often cited as a benchmark in Europe for combining CE governance with climate mitigation, showing that technologically advanced infrastructure and public engagement are mutually reinforcing (Waste Management World, 2023). Figure 1 illustrates Austria's Spittelau waste incineration plant, which integrates waste treatment with district heating and energy recovery. This example highlights how advanced CE strategies can serve both waste management and climate objectives simultaneously (FTI, 2022). By generating renewable energy and reducing methane emissions from landfills, such facilities demonstrate the dual environmental and economic benefits of CE-driven infrastructure.

Figure 1: The Spittelau waste incineration plant in Vienna, Austria, architect Friedensreich Hundertwasser
(Source: https://positionen.wienenergie.at/en/projects/spittelau-waste-incineration-plant/)

By contrast, Canada, the United States, and Australia demonstrate partial progress. In Canada, strong provincial-level EPR frameworks drive recycling in certain regions, but national performance remains uneven (CCME, 2018; Government of Canada, 1999). The U.S. continues to landfill around half of its MSW, reflecting fragmented federal–state governance and inconsistent adoption of EPR (EPA, 2021; EPA, 2025). Australia has made advances in specific states (Circular Economy Act, 2023; City Service, 2023) but lacks uniform national progress (DCCEEW, 2024; State of the Environment, 2023). These cases illustrate the limitations of fragmented or non-integrated approaches, where the absence of cohesive policy mixes results in slower gains in material recovery and climate benefits (D'Amato et al., 2020; Chennak et al., 2024).

Among transition and developing economies, such as Russia, China, and Georgia, CE strategies are in earlier stages. Russia has introduced a national waste law and nascent EPR schemes, but recycling remains below 10% (MNR, 2025; Rosstat, 2025). China, in contrast, has moved rapidly in recent years by pairing regulatory bans with EPR expansion and massive infrastructure investment (NPCC, 2008; MEE, 2022), achieving a circular material use rate of around 23% (Wenting et al., 2022).

Georgia has begun aligning its waste and climate policies with European standards. Its transition is anchored in the Waste Management Code (2014), the National Waste Management Strategy 2016–2030 (Ministry of Environmental Protection and Agriculture of Georgia, 2016; Rec-Caucasus, 2022), and **Vision 2030** (Government of Georgia, 2021; Vision 2030, 2022), alongside successive climate action plans (MEPA, 2025). These frameworks mark an important shift from a historically linear waste system toward circularity. However, challenges remain: the country's circularity rate is only 1.3% (Circularity Roadmap for Georgia, 2024), infrastructure for separate collection and recycling is underdeveloped (Waste, 2025; Wasteless, 2022), and enforcement of existing laws is weak (Florin et al., 2025). Georgia's 56 registered landfills (31 active) often lack environmental safeguards, while rural areas rely on informal disposal methods (Bazlidze et al., 2022). Despite these challenges, Georgia has set a target to increase its circularity to 9.1% in the next decade, a goal that—if supported by investment, monitoring, and public engagement—could significantly contribute to climate mitigation (Circularity Roadmap for Georgia, 2024).

The comparative overview underscores a central finding from the literature: policy mixes are critical. Jurisdictions that combine regulatory instruments (EPR, CE laws), fiscal or market-based incentives (subsidies, deposit-refund, PAYT), and citizen engagement mechanisms consistently outperform those that rely on isolated measures (Velenturf, & Purnell, 2021; Kirchherr et al., 2017; Morseletto, 2020). This integrated approach not only enhances material recovery but also strengthens the climate-mitigation potential of CE strategies (Ellen MacArthur Foundation, 2019; Abdirahman et al., 2025). For Georgia and other middle-income countries, the implication is clear: progress depends not only on introducing CE legislation but also on embedding it in a coherent policy mix that mobilizes economic incentives, builds enforcement capacity, and actively involves the public (Schröder, & Barrie, 2024; UNIDO, 2025).

Also, the comparative analysis of CE policies across different countries highlights how structured policy mixes can drive both recycling rates and climate benefits. As shown in Table 1, advanced economies such as Austria, Japan, and South Korea combine binding CE legislation with EPR schemes, fiscal incentives like pay-as-you-throw (PAYT) or deposit-refund systems, and active public engagement, resulting in high recycling rates (e.g., Austria ~63%, South Korea food waste >95%) and measurable reductions in GHG emissions. In contrast, transition economies, including Georgia, face limited infrastructure, low circularity (~1.3%), and weak enforcement, meaning the potential for climate benefits remains largely untapped.

Experiences from India and Turkey illustrate intermediate stages of CE implementation. In India, for example, *Challenges of implementing extended producer responsibility for plastic-waste management: lessons from India* explores how recent EPR rules face problems of weak enforcement, unclear roles for producers and local bodies, and overlap with informal recycling sectors (Gupta & Dash, 2023). Turkey's municipal solid waste management has also been evaluated in *Municipal Solid Waste Management: Circular Economy Evaluation in Turkey*, which finds recycling rates are still low, landfilling dominates, and greater public awareness, separate collection, and institutional planning are needed (Gokkurt Baki & Ergun, 2021). These examples show that coherent policy frameworks, supported by infrastructure, incentives, and citizen participation, are essential for CE to deliver climate mitigation.

For Georgia, adopting similar integrated CE strategies could substantially reduce GHG emissions. Landfills are currently the largest source of methane in the country. Evaluative studies suggest that increasing circularity from 1.3% to 9-10% over the next decade - through expanded EPR coverage, modernized recycling facilities, and enhanced waste separation—could lower methane emissions by 10-20% from the municipal waste sector, contributing directly to the country's Nationally Determined Contributions (NDCs). In addition, diverting organic and recyclable waste from landfills into recovery and composting pathways would also reduce CO_2-equivalent emissions, while stimulating local green jobs and resource efficiency. Thus, structured CE adoption in Georgia offers a practical pathway to combine economic, environmental, and climate benefits.

This review has examined how circular economy (CE) policies and waste legislation are being implemented across different jurisdictions, highlighting common parameters such as regulatory frameworks, Extended Producer Responsibility (EPR), economic and fiscal instruments, recycling performance, integration with greenhouse gas (GHG) reduction, enforcement capacity, and public engagement. The comparative analysis shows that advanced economies—such as Austria, South Korea, and Japan—achieve the most significant outcomes where CE is embedded in coherent policy mixes that combine binding legislation, EPR schemes, financial incentives, and citizen participation. These integrated approaches not only improve material recovery but also contribute directly to climate mitigation goals.

By contrast, fragmented or isolated measures, as observed in the United States, Canada, and Australia, tend to deliver uneven progress, underscoring the importance of alignment between national and subnational governance. Transition and developing economies such as Russia and Georgia remain in the early stages of CE adoption, while China demonstrates that rapid progress is possible when regulatory bans, EPR expansion, and infrastructure investment are pursued simultaneously.

In Georgia, CE implementation remains at an early stage. While the Waste Management Code (2014), the National Waste Management Strategy 2016–2030, and Vision 2030 have established a legal foundation, enforcement capacity is weak and recycling infrastructure remains limited to a few urban centers. The country's circularity rate is only 1.3%, far below the EU average of 11.5% (Circularity Roadmap for Georgia, 2024). Informal disposal methods still dominate in rural areas, and Extended Producer Responsibility (EPR) schemes cover only a narrow set of products. These structural gaps hinder both material recovery and climate co-benefits. Nonetheless, Georgia's target of reaching 9.1% circularity by 2030 demonstrates political commitment, which, if coupled with investments in infrastructure and stronger monitoring, could enable meaningful contributions to greenhouse gas (GHG) mitigation.

Estimating Georgia's GHG reduction potential highlights the importance of CE adoption. Landfills are currently responsible for nearly 8% of the country's total GHG emissions, primarily through methane (**NDC of Georgia (2021).** Updated Nationally Determined Contribution (NDC) of Georgia. Ministry of Environmental Protection and Agriculture of Georgia. Available at: https://ndcpartnership.org/country/geo (accessed 4 October 2025).Diverting 50% of biodegradable municipal waste from landfills to composting and biogas recovery could reduce waste-sector methane emissions by approximately 25–30% by 2030, depending on capture efficiency. Integrating these measures with recycling and material recovery would align CE strategies with Georgia's climate targets under the Paris Agreement.

Stakeholders' perspectives are critical to the success of CE transitions. Governments and municipalities play a central role in setting standards and ensuring enforcement, while private sector actors drive eco-innovation and Extended Producer Responsibility (EPR) schemes. Civil society organizations and NGOs can support awareness campaigns, while academia provides knowledge and monitoring tools. Importantly, citizen participation is indispensable: without public compliance in separate collection and recycling, CE policies cannot reach their targets. In Georgia, these perspectives are unevenly represented, suggesting the need for a more inclusive governance framework.
The key implication is that Georgia's transition will depend not only on adopting CE legislation but on embedding it within an integrated policy mix. Scaling infrastructure, strengthening enforcement, incentivizing private sector participation, and raising public awareness are essential steps. If supported by EU partnerships, financial investment, and eco-innovation, Georgia can leverage its early-mover advantage in the Caucasus to accelerate its circular transition and contribute meaningfully to climate change mitigation.

For Georgia, a realistic CE transition pathway can be envisioned in three phases: (i) short-term (2025–2030) — improve waste data collection, pilot separate collection projects, and expand EPR coverage; (ii) medium-term (2030–2040) — scale infrastructure, modernize recycling plants, and strengthen monitoring and enforcement capacity; (iii) long-term (2040–2050) — adopt digital product passports, integrate CE into industrial policy, and embed circularity in climate governance. This phased approach aligns with EU practices while recognizing Georgia's structural constraints.

5. Conclusion

Based on the comparative analysis, several recommendations emerge for Georgia and other transition economies pursuing a circular economy (CE):

1. **Develop integrated policy mixes** – Strengthen the Waste Management Code by combining regulatory instruments with fiscal and market-based incentives (e.g., deposit-refund, pay-as-you-throw) and robust EPR schemes to improve recycling and material recovery.
2. **Invest in infrastructure and enforcement** – Modernize waste collection, separation, and recycling facilities while enhancing monitoring and enforcement capacity at municipal and national levels.
3. **Foster public engagement and private-sector participation** – Scale awareness campaigns, education initiatives, and public–private partnerships to encourage citizen involvement and stimulate eco-innovation across industries.
4. **Align CE with climate objectives** – Integrate circularity indicators into national climate targets, prioritizing reductions in methane emissions from

landfills and promoting resource efficiency as a means of achieving greenhouse gas mitigation.

5. **Leverage international cooperation** – Use alignment with European Union directives and access to EU4Environment and Eastern Partnership programs to mobilize technical assistance, funding, and knowledge transfer.

References:

Ghosh, S. K., Parlikar, U. V., Karstensen, K. H. , (2022), Sustainable Management of Wastes through Co-processing, Book, Springer Nature Singapore Pte Ltd. 2022; https://doi.org/10.1007/978-981-16-6073-3

Sadhan Kumar Ghosh , Sannidhya Kumar Ghosh (2021), Conceptualising Circular Economy, Circular Economy: Recent Trends in Global Perspective (Ed. Book), Springer Nature Singapore Pte Ltd, 2021, pp 3-26, doi: https://doi.org/10.1007/978-981-16-0913-8_1

Sadhan Kumar Ghosh , Sannidhya Kumar Ghosh (2021), Circular Economy in India: Reduce, Reuse and Recycle through Policy Framework, Circular Economy: Recent Trends in Global Perspective (Ed. Book), Springer Nature Singapore Pte Ltd. 2021, pp 183-217, doi: https://doi.org/10.1007/978-981-16-0913-8_6

Abdirahman, A.A., Asif, M., & Mohsen, O. (2025). Circular economy in the renewable energy sector: review of growth trends, gaps and future directions. *Energy Nexus, 17*, 100395. https://doi.org/10.1016/j.nexus.2025.100395

Abid, I. et al. (2024). A systematic literature review on blockchain and digital product passports in the circular economy, DOI: 10.48550/arXiv.2408.11664

Basic Act for Establishing Sound Material-Cycle Society (2000). Government of Japan. Tokyo, Japan

Bazlidze, N., Shubitidze, E., Lobzhanidze, G. (2022). Developing circular economy in Georgia – the benefits, achievements, and challenges, Green and sustainable development , https://iset-pi.ge/en/blog/3169-developing-a-circular-economy-in-georgia-the-benefits-achievements-and-challenges

Bogner, J., et al. (2008). Mitigation of global greenhouse gas emissions from waste: Conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. *Waste Management & Research, 26*(1), 11–32. https://doi.org/10.1177/0734242X07088433

Building Canberra's Circular Economy (2023). ACT Circular Economy Strategy and Action Plan 2023-2030

CCME (2018). Zero Plastic Waste Strategy. Canadian Council of Ministers of the Environment: Ottawa, ON, Canada

Chennak, A., Giannakas, K. & Awada, T. (2024). On the Economics of the Transition to a Circular Economy. *Circ. Econ. Sust. 4*, 3007–3023 (2024). https://doi.org/10.1007/s43615-023-00297-8.

Circular Economy Act (2023). https://www.austlii.edu.au/cgi-bin/viewdb/au/legis/act/consol_act/cea2023181/ (accessed on 18 Aug. 2025)

Circularity Roadmap for Georgia (2024). https://forbes.ge/en/georgia-s-roadmap-to-circular-economy-a-regional-leader-s-transition-journey

City Service (2023). Building Canberra's Circular Economy. ACT Circular Economy Strategy and Action Plan 2023-2030. https://www.cityservices.act.gov.au/__data/assets/pdf_file/0020/2272331/ACT-Circular-Economy-Strategy-access.pdf (accessed on 10 Aug. 2025)

D'Amato, D., et al. (2020). Circular economy: Current narratives and future pathways. *Ecological Economics, 170*, 106624. https://doi.org/10.1016/j.ecolecon.2019.106624

DCCEEW (2024). National Waste Policy Action Plan. 2024. https://www.dcceew.gov.au/environment/protection/waste/publications/national-waste-policy-action-plan (accessed 18 Aug. 2025)

DiSilvio, S., Ozerov, A., & Zhou, L. (2023). https://arxiv.org/abs/2311.16585

Ducuing, C. & Reich, R. H., (2023). Data governance and digital product passports: a case study, Competition and Regulation in Network Industries 24, 1–20, DOI: 10.1177/17835917231152799

Elizbarashvili, M., Khardziani, T., Maisuradze, R., Tatishvili, M. (2018). Mountain environment and population in Georgia: case study of Upper Svaneti. *International Journal of Sustainable Development and World Ecology, 25*(4), pp. 362–370. https://doi.org/10.1080/13504509.2017.1417182

Elizbarashvili, E.Sh., Elizbarashvili, M.E. (2002). Reaction of some types of landscapes of Transcaucasia to the global warming. *Izvestiya Akademii Nauk Seriya Geograficheskaya, 5,* 52–56.

Ellen MacArthur Foundation (2019). Completing the Picture: How the Circular Economy Tackles Climate Change. Ellen MacArthur Foundation

EPA (2021). U.S. EPA. Advancing Sustainable Materials Management: 2021 Fact Sheet. Available online: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling (accessed on 18 August 2025)

EPA (2025). U.S. Environmental Protection Agency (EPA). Resource Conservation and Recovery Act (RCRA). Available online:

https://www.epa.gov/rcra (accessed on 18 August 2025)

European Commission (2020). Circular Economy Action Plan for a Cleaner and More Competitive Europe. Brussels: European Commission.

European Environment Agency (2023). https://www.eea.europa.eu/en/analysis/publications/economic-instruments-and-separate-collection

Florin, C.M., Ishchenko, V., Iordachi, V., Ivanova, V. & Dzebisashvili, N. (2025). Circular Economy and Waste Management in Eastern Europe. Circular Economy, 1 (1), Academy of Sciences and Arts of the Republic of Srpska, Banja Luka, Monograph, pp.57-95, 978-99976-42- 87-5. ff10.7251/PRB2401057Mff. ffhal-05045935

France's Ministry for Ecological Transition (2022). Anti-Waste and Circular Economy Law, Paris, https://www.ellenmacarthurfoundation.org/circular-examples/frances-anti-waste-and-circular-economy-law

FTI (2022). The Austrian circular economy strategy. 2022. https://fti-ressourcenwende.at/en/strategy/austrian-circular-economy-strategy/ (accessed on 18 Aug. 2025)

Ghosh, S. K., (2020), Circular Economy: Global Perspective (Ed. Book), Springer Nature Singapore Pte Ltd. 2020, https://doi.org/10.1007/978-981-15-1052-6

Ghosh, Sadhan Kumar, and Sannidhya Kumar Ghosh. "Circular Economy Catalysing Decarbonization." Circular Economy Adoption: Catalysing Decarbonisation Through Policy Instruments. Singapore: Springer Nature Singapore, 2023. 3-33. DOI. 10.1007/978-981-99-4803-1_1

Gokkurt Baki, O., & Ergun, O. N. (2021). Municipal Solid Waste Management: Circular Economy Evaluation in Turkey. *Environmental Management and Sustainable Development*, 10(2), 79-92. https://doi.org/10.5296/emsd.v10i2.18448

Government of Canada (1999). Canadian Environmental Protection Act, 1999; CEPA Registry: Ottawa, ON, Canada

Government of Georgia (2021). Updated Nationally Determined Contribution (NDC) of Georgia. Ministry of Environmental Protection and Agriculture of Georgia

Gupta, D., & Dash, S. (2023). Challenges of implementing extended producer responsibility for plastic-waste management: Lessons from India. *Social Responsibility Journal*, 19(9), 1595-1612. https://doi.org/10.1108/SRJ-08-2022-0326

Gupta, Y., & Sahay, S. (2015), Review of extended producer responsibility: A case study approach, 2015. *Waste Management & Research 33*(7):595–611, DOI: 10.1177/0734242X15592275

Hakola, L. et al. (2025). Smart Tags as Enablers for Digital Product Passports in Circular Electronics Value Chains. *Circular Economy and Sustainability 5*(3):2033-2055, DOI: 10.1007/s43615-025-00500-y

Hartley, K., Schülzchen, S., Bakker, C. A., & Kirchherr, J. (2023). policy framework for the circular economy: Lessons from the EU. *Journal of Cleaner Production, 412*, 137176. https://doi.org/10.1016/j.jclepro.2023.137176

ILO (2023). Decent Work in the Circular Economy: An Overview of the Existing Evidence Base, https://www.ilo.org/publications/decent-work-circular-economy-overview-existing-evidence-base

IPCC (2022). Mitigation of Climate Change. 2022. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK

IPCC (2021). Climate Change 2021: The Physical Science Basis. Cambridge University Press. https://doi.org/10.1017/9781009157896

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., & Hekkert, M. (2018). Barriers to the : Evidence From the European Union (EU). *Ecological Economics, 150*, 264-272. https://doi.org/10.1016/j.ecolecon.2018.04.028

Kirchherr, J., Reike, D., Hekkert, M. (2017). Conceptualizing the Circular Economy: An Analysis of 114 Definitions. *Resour. Conserv. Recycl. 127*, 221–232, https://doi.org/10.1016/j.resconrec.2017.09.005

MEE (2022). Ministry of Ecology and Environment (China). Report on the State of China's Ecology and Environment 2022. Available online: http://english.mee.gov.cn (accessed on 18 August 2025)

MEPA (2025). 2021-2023 Action Plan of Georgia's 2030 Climate Strategy. https://mepa.gov.ge/En/Files/ViewFile/50122 (accessed on 19 August, 2025)

MESK (2018). Ministry of Environment (South Korea). Framework Act on Resource Circulation; Seoul, South Korea, 2018

Mhatre, P., Panchal, R., Singh, A., & Bibyan, S. (2021). systematic literature review on the circular economy initiatives in the European Union. *Sustainable Production and Consumption, 26*, 187-202. https://doi.org/10.1016/j.spc.2020.09.008

Ministry of Environmental Protection and Agriculture of Georgia (2016). National Waste Management Strategy 2016–2030. https://rec-caucasus.org/wp-content/uploads/2022/12/National-Waste-Management.pdf (accessed on 18 August 2025)

MNR (2025). Russian Federation. National Project "Ecology". Available online: http://www.mnr.gov.ru (accessed on 18 August 2025)

Moalem, R. M., & Ghosh, S. K. (2024). Value Creation from Waste: Roles and interface between the Informal and Formal waste Sectors in India and Denmark in a just circular transition. The Journal of Solid Waste Technology and Management, 50(4), 711-724. doi: https://doi.org/10.5276/jswtm/iswmaw/50S1/2024.711

Morseletto, P. (2020). Targets for circular economy. *Resources, Conservation and Recycling, 153*, 104553. https://doi.org/10.1016/j.resconrec.2019.104553

NDC of Georgia (2021). https://ndcpartnership.org/country/geo (accessed on 18 September 2025)

NPCC (2008). National People's Congress of China. Circular Economy Promotion Law; Beijing, China. https://www.lawinfochina.com/display.aspx?id=7025&lib=law#:~:text=The%20Circular%20Economy%20Promotion%20Law,force%20on%20January%201%2C%202009 (accessed on 18 August 2025).

OECD Economic Outlook. (2023). ISSN: 1609-7408 (Online). https://www.oecd.org/en/publications/serials/oecd-economic-outlook_g1ghgh13.html (accessed on 04.09.2025)

OECD (2022). https://www.oecd.org/content/dam/oecd/en/publications/reports/2022/12/deposit-refund-systems-and-the-interplay-with-additional-mandatory-extended-producer-responsibility-policies_c92a063b/a80f4b26-en.pdf

OECD (2021). Waste Management and Circular Economy in South Korea. 2021. OECD Environmental Performance Review: Korea

Parliament of Georgia (2015). Waste Management Code of Georgia (No. 2994-RS). Legislative Herald of Georgia, https://environment.cenn.org/app/uploads/2016/06/Waste-Management-Code_FINAL_2015.pdf (accessed on 19 September 2025)

PWC (2025). Digital infrastructure's defining moment on climate, https://www.pwc.com/gx/en/industries/tmt/digital-infrastructures-defining-moment-on-climate.html#:~:text=To%20meet%20their%20publicly%20declared,case%20for%20investment%20in%20decarbonization

Rahmani, D., Atasu, A., & Subramanian, R. (2020). https://www.scheller.gatech.edu/directory/research/operations-management/rahmani/pdf/rahmani_etal_2020.pdf

Rec-Caucasus (2022). National Waste Management Strategy 2016-2030 and National Waste Management Action Plan 2022-2026, https://rec-caucasus.org/wp-content/uploads/2022/12/National-Waste-Management.pdf (accessed on 19 August 2025)

Rosstat (2025). Russian Statistical Agency. Waste Management Indicators 2022. Available online: https://rosstat.gov.ru (accessed on 18 August 2025)

Sadhan Kumar Ghosh , Sannidhya Kumar Ghosh (2021), Conceptualising Circular Economy, Circular Economy: Recent Trends in Global Perspective (Ed. Book), Springer Nature Singapore Pte Ltd, 2021, pp 3-26, doi: https://doi.org/10.1007/978-981-16-0913-8_1

Schröder, P., & Barrie, J. (2024). How the circular economy can revive the Sustainable Development Goals, Priorities for immediate global action, and a policy blue for the transition to 2050, Environment and Society Centre, https://www.chathamhouse.org/sites/default/files/2024-09/2024-09-19-how-the-circular-economy-can-revive-the-sdgs-schr%C3%B6der-barrie.pdf

Schröder, P. (2020). Promoting a Just Transition to an Inclusive Circular Economy; Energy, Environment and Resources Programme, https://www.chathamhouse.org/sites/default/files/2020-04-01-inclusive-circular-economy-schroder.pdf

Schröder, P., et al. (2020). The Circular Economy in the European Union. In: Murray, A., Nilsson, L., & T. Russell (Eds.), Handbook of the Circular Economy, pp. 89–104. Edward Elgar, https://doi.org/10.4337/9781788972727.00014

Sound Material-Cycle Society Indicators (2022). Ministry of the Environment (Japan). Available online: https://www.env.go.jp (accessed on 18 August 2025)

State of the Environment (2023). Report, https://www.actsoe2023.com.au/ (accessed on 18 Aug. 2025)

UNEP, (2019). Global Waste Management Outlook. United Nations Environment Programme.

UNIDO (2025). Circular Economy and Digitalization, Working Paper, https://www.unido.org/sites/default/files/unido-publications/2025-06/Circular%20Economy%20and%20Digitalization.pdf

Velenturf, A.P.M., & Purnell, P. (2021). Principles for a sustainable circular economy. *Sustainable Production and Consumption, 27*, 1437-1457, https://doi.org/10.1016/j.spc.2021.02.018

Vision 2030 (2022). Georgia's Development Strategy, Government of Georgia, Resolution #517, 2022, https://www.matsne.gov.ge/ka/document/view/5604706?publication=0

Waste Management World, (2023). Austria is model country for recycling. 2023. https://waste-management-world.com/resource-use/eu-waste-early-warning-report (accessed on 18 Aug. 2025)

Waste (2025). Waste Management Company of Georgia, Municipal Landfills, https://waste.gov.ge/ka/?page_id=1027&lang=en (accessed on 20 August 2025)

Wasteless (2022). Waste Management Challenges in Georgia, https://wasteless.ge/full_new/en/84/Waste-Management-Challenges-in-Georgia (accessed on 19 August 2025)

Wenting, M., Hoppe, Th., De Jong, M. (2022). Policy Accumulation in China: A Longitudinal Analysis of Circular Economy Initiatives. *Sustainable Production and Consumption, 34*, 490-504, https://doi.org/10.1016/j.spc.2022.10.010

Wilson, D.C., Velis, C. and Cheeseman, C. (2006). Role of Informal Sector Recycling in Waste Management in Developing Countries. *Habitat International, 30*, 797-808, http://dx.doi.org/10.1016/j.habitatint.2005.09.005

World Bank (2020), https://documents1.worldbank.org/curated/en/099640003102239957/pdf/P1709940b3dbd3092083b208e60bcd5719a.pdf (accessed on 17 August 2025)

World Bank (2018). What Waste 2.0: Global Snapshot of Solid Waste Management to 2050. World Bank: Washington, DC, USA, https://documents1.worldbank.org/curated/en/697271544470229584/pdf/132827-PUB-9781464813290.pdf (accessed on 17 August 2025)

Yang, M., Chen, L., Wang, J. et al. (2023). Circular economy strategies for combating climate change and other environmental issues. *Environ. Chem. Lett. 21*, 55–80, https://doi.org/10.1007/s10311-022-01499-6.

Zocco, F., & Malvezzi, M. (2024). Circular Economy Design through System Dynamics Modeling, Dynamical Systems, https://doi.org/10.48550/arXiv.2411.13540.

Circular economy inspired utilization of tea waste in dye pollution mitigation

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ABSTRACT

The use of industrial dyes in various sectors, especially, paper and textile, where synthetic chemical dyes are predominantly used, has often posed environment challenges. The given study evaluates the recycling potential of tea waste as a dye (methylene blue) adsorbent and a substrate for production of industrially important enzymes. Evaluative experiments on adsorption ability of tea waste showed more than 90% adsorption under optimized incubation conditions. A successive use of dye-adsorbed tea waste as solid substrate for the growth and production of industrially important enzyme, laccase, by Phanerochaete chrysosporium, one of the most industrially relevant white rot fungi, exhibited promising results. Significant laccase activity was observed for the dye adsorbed tea waste, under optimized conditions of solid state fermentation (SSF). Further, the resultant spent fungal-tea waste-biomass was subjected to a 2nd cycle of adsorption & enzyme production. More than 75% dye decolorization ability and more than 45% laccase activity was retained for spent fungal-tea-waste-biomass after 2nd cycle of adsorption-fermentation. Tea waste can be a good option of a low cost adsorbent for environmental pollutants like harmful synthetic dyes. Multiple cycles of adsorption-enzyme production using such low cost substrates offer an opportunity to add value to such natural waste and also additionally decrease the cost of production of industrially relevant enzyme, laccases, in the light of circular economy principles. Further investigations on substrate modification, cost estimates, combinatorial approaches, etc., to enhance bioremediation potential of tea waste and potential integration into existing treatment processes will help in better exploration of tea waste in bioremediation.

Keywords: Dye pollution, Laccase, Recycling, Tea waste, Bioremediation, Circular economy.

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1. Introduction

Due to increment in the urbanization and industrialization a huge increase in the environmental pollution is taking place every day due to use and manufacturing of polluting chemicals, discharge of pollutants in the environment, faulty effluent practices, etc. Industrial dyes are commonly used in food, cosmetics, paper, plastics, and textile industries. The textile industry is one of the biggest users of dyes

(Gomez et al., 2007, Das et al., 2023) with a large portion of it being released as a waste in the industrial effluent (Gupta et al., 2013). The chemically synthesized (synthetic) dyes are thus important contributors to the water pollution and associated toxicity (Pang et al., 2013).

Azo dyes are widely used in textile, pharmaceutical, cosmetic and food industries (Asad et al., 2006, Alzain et al., 2023). Disperse dyes are commonly use to dye cellulose acetate, nylon and other hydrophobic fibers (Molinari *et al.,* 2004). Due to their non-degradable nature (owing to their synthetic origin and aromatic structure), such dyes persist in the nature when disposed of into the environment through industrial effluents and become a source of menace for the environment and various life forms. Many have known to impact adversely on human health as most of them are water soluble and can readily be absorb through skin contact leading to severe health problems (Lellis et al., 2018, Alzain et al., 2023). Thus, there is need of exploration of the methods that can be reliably used to remove these types of the harmful chemicals from the water leading to the reduction in the water pollution. Various methods are used for dye removal from wastewater but many are often associated with limitations like, high cost, limited range of applicability, high sludge generation, production of toxic byproducts, etc. (Ghoreishi and Haghighi, 2003, Pang et al., 2013).

Adsorption has been found to be an effective way for dye removal (Yagub et al., 2014, Das et al., 2019, Wong et al., 2020) and some adsorbents like, activated carbon are being used (El maguana et al., 2020, Sugumaran *et al.,* 2012). Adsorbents like, fly ash, chitosan, zeolites, paper pulp also allow adsorption of metal ions and that of dyes onto their surfaces (Badawi et al., 2021)), thereby holding potential of solving dual problems of waste treatment simultaneously. Adsorbents derived from various materials like fly ash, chitosan, zeolites, paper pulp, agro-industrial waste are being prominently used for dye adsorption (Rafatullah *et al.,* 2010, Unuabonah *et al.,* 2009, Dawood and Sen, 2012, Yagub et al., 2012, Abbas et al., 2020) nowadays due to their environment friendly nature and cost efficiency associated. The pith of banana, ground nut shell, sugarcane bagasse, fruit stones, rice husk, wood, tea waste, etc. (Gupta et al.,2009) are few important sources of adsorbents derived from agro-industrial waste. Methylene blue, a commonly used industrial dye also been evaluated for its adsorption on various adsorbents (Rafatullah et al., 2010, Unuabonah et al., 2009).

Tea waste is the material left after the consumption of the tea in any form. The 'Tea board of India' defines the tea waste as 'Tea which does not confirm to the specification for tea laid down under the Prevention of Food Adulteration Act,1954 (37 of 1954) but does not include green tea or green tea stalks (Tea board of India). It is rich in organic matter and has been used in applications like, plant culturing, clay brick production, compost, production of edible mushrooms, microbial fermentation, remediation of heavy metal pollution, even as heavy metal adsorbents (Guo et al., 2021). A few estimations suggest that global per capita consumption of tea is second only to packaged drinking water and is expected to be 7.4 million metric tonnes by 2025 (https://statista.com). India is second only to China in producing tea. This also means that rising demand for tea and tea based products would ultimately translate into huge quantities of tea wastes generated as the natural degradation of tea is difficult (Debnath et al., 2021). Hussain et al., (2018) report that around 190,000 tonnes of tea waste is generated annually. Though some researchers report the use of tea waste for adsorption of synthetic dyes (Foroughi-Dahr et al., 2015, Pirbazari et al., 2014, Vithalkar and Jugade 2023), but these are limited evaluations and need to be further investigated for large scale applicability. Tea waste, due to its organic content and rich nutritional profile, is rich can be a promising substrate for microbial fermentation as well (Xu et al., 2020). *Phanerochaete chrysosporium* is an important white rot fungus capable of aerobic dye degradation (Kumar et al., 2013). It produces a variety of enzymes including laccases, manganese peroxidases, lignin peroxides (Tan et al., 2013) which cause the degradation of complex dye molecule into simple structures, thereby aiding in reducing environmental pollution due to harmful chemical dyes.

Keeping in view the need for sustainable solutions to industrial issues, and the rapid requirement for transitioning from linear to circular economy in the light of Sustainable Development Goals (SDGs), we attempt to evaluate the integration of a simple adsorption process using natural agro-industrial residue, tea waste and ability of *Phanerochaete chrysosporium* to utilize resultant dye adsorbed tea waste as a substrate for laccase production in multi-recycling system. Some researchers have reported the use of tea waste in dye decolorization and laccase production (Vithalkar and Jugade 2023, Xu et al., 2020), but studies on using both, dye decolorization and laccase production (so as to reutilize spent adsorbent) in a cyclic approach, has been rarely reported. Very few evaluations multiple adsorption-fermentation cycle approach to dye bioremediation has been attempted on wheat bran, wheat straw, rice husk and their combinations (Singh et al., 2022, Das et al., 2023), but to the best of our knowledge, tea waste has not been tested as a substrate for growth of *Phanerochaete chrysosporium* and production of industrially important enzymes (laccase). Some reports suggest use of modified (physical or chemical) tea waste, but our study focuses on simple, unmodified tea waste. Thus, present work explores the adsorptive properties of tea waste and also the use of dye adsorbed tea waste as substrate for fungal growth and enzyme production.

2. Materials and Methods

All the chemicals and nutrient media (except tea waste) were of analytical grade and were purchased from Loba-chemie, Mumbai, India.

2.1 Microorganisms

The glycerol stock of *Phanerochaete chrysosporium* MTCC 787 was revived on Malt extract agar medium at 28°C for 5 days. Subsequently, the culture grown and was preserved at 4°C for the further use. For long term preservation, spores and mycelium of the test fungus were stored in glycerol stocks (Singh et al., 2009, Richter et al., 2010).

2.2 Adsorbent

Tea granules (TG) and tea leaves (TL) were purchased from local market of Phagwara, Punjab, India. The collected materials were boiled, sieved and then washed with distilled water several times. The collected materials were then dried at 60°C for 48-60 hours and sieved (100-500 µm) to obtain uniform sized particles (Pirbazari *et al.,* 2014). The resultant solid dry tea wastes were stored in ziplock bags till further use in a clean and dry place.

2.3 Evaluation of tea waste as adsorbent and fermentation substrate

The tea waste viz., tea granules and tea leaves based was subjected to multiple cycles of Adsorption-Fermentation (each comprising of 1 step each of Adsorption and Fermentation). The scheme of the methodology is given below:

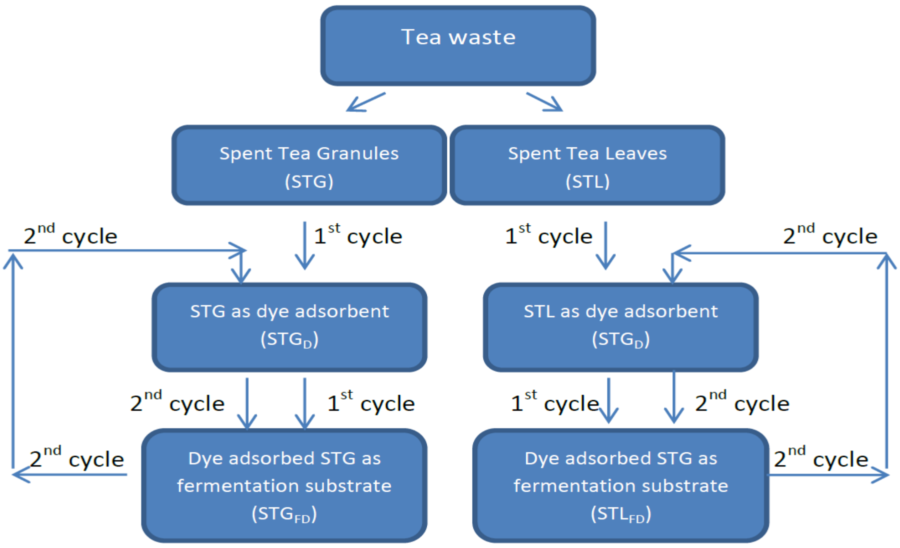


Figure 1: Schematics of Adsorption-Fermentation adopted

2.4. 1st cycle of adsorption-fermentation

2.4.1 Effect of incubation variables on the MB decolorization by tea waste

The stock solution (10 mg/1000 mL of distilled water) was diluted to different concentrations and 0.5 gm, each of adsorbents (STG and STL), as prepared above, were added to 100 ml of the resultant dye solutions. The effect of different variables was checked using the 'one factor at a time' approach. The dye: adsorbent ratio was maintained (explained as above) and incubated at 50-90°C for 120 mins. The samples were withdrawn at desired intervals and spectrophotometrically analyzed at 664 nm. The dye adsorption was determined as (Lima et al., 2024, Das et al., 2019, Kalme et al., 2007, Pirbazari et al., 2014):

% Dye adsorbed = (I-F/I) X 100

Where, I= Initial dye concentration (mg/L)
F= Final dye concentration (mg/L)

Similarly, the influence of contact time, in minutes (30, 60, 90, 120, 150), adsorbent dose, in grams (0.25, 0.5, 0.75, 1.0, 1.25, 1.5), pH (5.0, 6.0, 7.0, 8.0) was also determined under desired conditions (Pirbazari et al., 2014, Foroughi-Dahr et al., 2015)

2.3.2 Dye decolorization under optimized experimental conditions and solid substrate preparation for fermentation

The dye decolorizing ability of STG and STL were subsequently determined under experimental conditions as optimized above. The residual dye adsorbed substrates (STG_D & STL_D) were subjected to a gentle single wash with distilled water and then dried at 90ºC for 4 hrs. The dried substrates were gently crumbled to obtain uniform particles and stored in Ziploc bags at room temperature under dry conditions till future use.

2.3.3 Evaluation of dye adsorbed spent tea granules and spent tea leaves (STG_D & STL_D) waste as substrate for laccase production under solid state fermentation (SSF)

One factor at a time (OFAT) approach was used to determine optimum fermentation conditions for laccase production using STG_D & STL_D as solid substrate. The dye adsorbed substrates (STG_D and STL_D) were added to 250 ml Erlenmeyer flask, followed by addition of nutrient salt solution which was, $(NH4)_2SO_4$ (0.14%), KH_2PO_4 (0.2%), $MgSO_4.7H_2O$ (0.03%), $CaCl_2$ (0.03%), $FeSO_4.7H_2O$, (0.002%), $ZnSO_4.7H_2O$ (0.002%), $MnSO_4.7H_2O$ (0.002%), $CoCl_2$ (0.002%), at pH 6 in the ratio (Ivanka et al., 2010). The prepared flasks were steam sterilized, aseptically inoculated with 2 fungal discs (0.25 mm diameter each) by disc inoculation method and then incubated at 37ºC for desired incubation period (0 to 12 days) (Gupte et al., 2007). After desired incubation period, 15 mL of distilled water to each flask and the contents crushed with the stirring rod and mixed using a rotary shaking incubator for 10 minutes at 200 rpm. This mixture was then filtered through 3-4 layers of muslin cloth and the extract was centrifuged at 4000 rpm for 15 min. The supernatant was treated as crude enzyme (Muthezhilan et al., 2007; Singh et al., 2009). The enzyme activity was determined and the enzyme activity was expressed as International units (U). 1 U is defined as the amount of laccase enzyme required to oxidize 1micromole of the Guaiacol per minute. Similarly, the influence of incubation temperature, pH, inoculum size (Desai et al., 2011, Tekere et al., 2001, Ozmen and Yesilada, 2012, Nandal et al., 2013) was also determined.

2.4 2nd cycle of Adsorption-Fermentation

The spent tea wastes, STG_D & STL_D was subjected to optimum SSF conditions of incubation, time, temperature, pH and inoculum size and the laccase activity was finally determined. Thereafter, the left over spent fungal-tea-biomass (STG_{FD} & STL_{FD}) obtained from the current laccase production medium under optimized conditions was again evaluated for potential reuse in dye decolorization process. The steps were repeated as above.

3 Result and Discussion

3.1 1st cycle of adsorption-fermentation

3.1.1 Effect of process variables on decolorization of Methylene blue dye by tea waste

The maximum dye decolorization (91.5%) for STG was observed at 70ºC, STL showed maximum dye decolorization (89%) at 60ºC. Both STG (74%) and STL (61%) exhibited the poorest dye decolorization at 50ºC (Table 1). Pirbazari et al., 2014 reported tea waste 94% dye decolorization at around 40ºC, which indicates a higher temperature requirement in the current study to achieve more than 90% dye removal, which indicate variable adsorption kinetics involved. Khosla et al., (2011) showed complete (100%) removal of Basic red dye with modified tea waste (SDS treated) TW, which may be because of the deposition of the more of the anionic charge on the surface of the tea molecules on SDS treatment of tea waste which favors the dye binding. Overall, STL shows the lesser temperature to exhibit comparable dye decolorization as compared to STG. However, STG shows better adsorption at all temperatures tested as compared to STL. Increase in the temperature increases the diffusion rate of the molecules and also causes decrease in the viscosity of the solution. This also indicates that this adsorption process is endothermic in nature. However the decrease in the absorption after 70ºC is found because the temperatures start reaching to boiling point which may cause the removal of adhered color of tea (Uddin et al., 2009).

On evaluating the effect of contact time on dye colorization, it was observed that decolorization was rapid in the first 30 minutes but slowed down and gradually reached saturation (Table 1). This may be because initially, the mass driving force is high due to high concentration of dye aiding in overcoming of resistance to dye adsorption (Pirbazari et al., 2014). The best decolorization was achieved for 120 mins of incubation for both STG (91.6%) as well as STL (89%) and the poorest for 30 minutes of incubation for both STG (89%) as well as STL (68%), though the most active dye uptake was observed in the 1st 30 mins of incubation time), indicating direct effect of temperature rise on dye adsorption ability (Akar et al., 2013). In comparision Lima et al. (2024), who reported 50 mins as optimum time for maximum adsorption of crystal violet while using spent tea leaves as adsorbent, we found 120 mins as optimum (almost double the time reported by Lima et al., 2024) for maximum adsorption of methylene blue. This may be due to the interactive properties of the different dyes involved. Auta et al., (2011) also reported similar temperature effect on modified tea waste activated carbon for adsorption of acid blue 25.

The adsorbent dose also plays a crucial role in determining the extent of dye decolorization. With an increase in the amount of adsorbent, increment in dye decolorization was observed (Table 1). 1.25 gm of adsorbent showed best decolorization for both STG (94.3%) as well as STL (93%) as adsorbents, also indicating that dye decolorization was similar in both cases with only STG showing 1.37% better decolorization ability than STL. The minimum dye decolorization was 84% & 73.8% for STG and STL, respectively with 0.25 gm of adsorbent dose suggesting dose dependent dye decolorization, which may be due to higher availability of adsorption sites for dye molecules to bind (Khosla et al., 2011). Akar et al., (2013) showed that activated carbon from spent tea leaves exhibited increased dye adsorption with increment in adsorption dose from 0.8 to 6 gm.

Maximum dye decolorization (92%) for STG was seen at pH 7, while that for STL (93.8%) was observed at pH 8. The effect was least at pH 5, reporting less than 90% dye decolorization for both adsorbents. Methylene blue is a cationic dye which exists in aqueous solution in the form of positively charged ions. The charge on the surface of adsorbent greatly influences the dye removal ability of adsorbents (Pirbazari et al., 2014). Khosla et al., (2011) also found the great influence of pH on the basic red dye adsorption by tea waste. However, in this case maximum adsorption (96%) of basic red dye at pH 4 with modified (SDS treated tea waste).

Table 1: Effect of incubation variables on the MB decolorization by tea waste

Incubation Variables		**Dye Decolorization (%)**	
		STG	**STL**
Incubation Temperature (°C)	50	74.0	61
	6	81.0	89
	70	91.5	81
	80	86.2	80
	90	84.0	74
Incubation conditions: Dye concentration (mg/L): 10; Adsorbent dose (gm): 0.5; Time (minutes) : 120; pH : 7.0			
Contact time (mins)	30	89	68
	60	90	79
	90	91	83
	120	91.6	89
	150	90	81
Incubation conditions: Dye concentration (mg/L) : 10; Adsorbent dose (gm) : 0.5; Temperature (° C) : 70; (STG) and 60 (STL); pH : 7.0			
Adsorbent dose (gm)	0.25	84	73.9
	0.50	90	81.9
	0.75	91.8	86.6
	1.0	93.8	91.2
	1.25	94.3	93
	1.50	89	84
Incubation conditions: Dye concentration (mg/L): 10; Time (mins): 120; Temperature (° C) : 70 (STG) and 60 (STL); pH : 7.0			
Incubation pH	5	82%	89%
	6	91%	91.2%
	7	92%	92.5%
	8	88%	93.8%
Incubation conditions: Dye concentration (mg/L) : 10; Time (minutes) : 120; Temperature (° C) : 70 (TG) and 60 (TW); Adsorbent dose (grams) : 1.25; ***STG:** Spent tea granules; **STL**: Spent tea leaves			

3.1.2 Decolorization of methylene blue (MB) under optimized incubation conditions and preparation of dye adsorbed tea waste (STG_D and STL_D) for use as solid substrate in laccase production by *Phanerochaete chrysosporium* MTCC 787

STG showed the best dye decolorization capacity at 91.3% under the optimized temperature of 70ºC, in 120 minutes at a pH of 7 and dye concentration of 10 mg/L. STL showed the maximum dye decolorization of 92% under the optimized incubation temperature of 60ºC for 120 minutes at a pH of 8 and a dye concentration of 10mg/L. The current study showed much higher than that reported for another basic dye, crystal violet (88%) with wheat bran as adsorbent (Das et al., 2019). Bansal et al. (2020) reported 95% adsorption of Eriochrome Black-T (EBT) using acid-modified tea waste while Nakamura et al. (2022) evaluated 21 types of tea waste for adsorption of ionic dyes. Tea residues contains various active organic groups like, carboxylic acids, phenolics, hydroxyl groups, and oxyl groups and with a porous structural properties, tea residues are effective adsorbents for metal ions and small molecules like, dyes (Cakmak et al., 2024)

3.2 Dye adsorbed tea waste (STG_D and STL_D) as solid substrate for laccase production

When evaluated as substrates for laccase production under SSF (Table 2), STG_D showed highest laccase activity (98.5 U/mL) on the 7th day of the incubation but for STL_D the laccase activity was best (194 U/mL) was shown after the 8th day of the incubation. When evaluated for influence of variable incubation temperatures, the laccase activity was best at 29±2ºC for both substrates (STG_D: 96.59 U/mL; STL_D: 191.2 U/mL) used. Similar observations have been made earlier for laccase production by *Trichoderma sp.* (Gochev et al., 2007). The highest enzyme activity in response to variable inoculum size showed that an inoculum size of 1.5 cm (6 fungal discs, each of 0.25 cm) was optimum for both STG_D (96.4 U/mL) and STL_D (192.1U/mL) as solid substrates. With the smallest inoculum size investigated (0.25 cm), the enzyme activity was around 43% & 40% for STG_D and STL_D lesser than the optimum observed. Elshafei et al. (2012) also indicated progressively increased laccase production with increase in the size of inoculum. As pH of the growth medium greatly influences laccase production, the influence of pH on STG_D and STL_D based fermentation was checked. The maximum laccase production was seen for pH 6 for both substrates. A pH of 5 has been found to be optimum by others (Irshad et al., 2011, Elshafei et al., 2012) also investigate the pH effect on enzyme production and found 5.5 as optimum pH for the laccase production. Interestingly, a slightly different approach, where tea waste was first used as substrate for laccase production, followed by the use of the resultant 'dry fermented tea residues' as crude enzyme in decolorization of malachite green was reported by Xu et al. (2020). Laccase production by *Trametes versicolor* using tea residues exhibited 31.2 U/g dry substrate after 8 days of incubation (Xu et al., 2020) under optimized conditions of SSF. Crude laccase enzyme was produced from Megasporoporia sp., under solid state fermentation conditions (Jafari et al., 2023) but in the presence of an inducer, bi-phenyl and a control without the presence. The investigators evaluated the laccase enzyme decolorizing effect on different azo dyes while evaluating the effect in the presence/absence of biphenyl. In our study, though, we did not use any specific additional inducer. Also, decolorization was directly related to laccase production but in our study, we focused on using dye adsorbent (tea waste) as a substrate for laccase production so as to provide a solution to reduce spent adsorbent waste and re use it for producing something economoically valuable, as laccase enzyme.

Table 2: Effect of SSF conditions on laccase production using dye adsorbed tea waste (STG_D and STL_D)

Fermentation parameters	**Laccase activity (U/mL)**	
Incubation period	**STG_D**	**STL_D**
1	42.78±0.9	89.15±0.2
2	58.8±0.7	93.7±0.6
3	62.6±1.4	121.1±1.1
4	68.11±1.2	128.8±0.7
5	74.2±0.2	140.1± 0.5
6	78.9±1.7	149.9±0.3
7	98.5±1.1	183.7±1.0
8	69.2±0.1	194.0±0.4
9	58±1.0	182±0.9

INCUBATION CONDITIONS: Inoculum size (cm): 2 fungal discs (0.25 cm each); pH: 6.0; Substrate: moistening agent: 1:3; Incubation temperature (°C): 37±2		
Incubation Temperature (°C)	**STG$_D$**	**STL$_D$**
14±2°C		
25±2 °C	61.5±1.3	146.18±1.7
29±2 °C	96.9±0.7	191.2±1.4
37±2 °C	83.4±1.1	185.6±0.6
INCUBATION CONDITIONS: Inoculum size (cm) : 2 fungal discs (0.25 cm each; pH : 6.0; Substrate: moistening agent: 1:3; Incubation duration (days): 7 (STG) and 8 (STL)		
Inoculum size (cm)	**STG$_D$**	**STL$_D$**
0.25 (2 fungal discs)	54.9±1.1	116.4±1.2
0.5 (2 fungal discs)	89.15±0.2	134.2±0.3
0.75 (3 fungal discs)	93.2±0.7	170.5±1.7
1.5 (6 fungal discs)	96.4±1.6	192.1±1.4
2.0 (8 fungal discs)	85±1.8	179±1.0
INCUBATION CONDITIONS: pH: 6.0; Substrate : moistening agent: 1:3; Incubation period (days) : 7 (TG) and 8 (TL); Incubation temperature (°C) : 29±2.		
Incubation pH	**STG$_D$**	**STL$_D$**
4.0		
5.0	83.7± 0.1	172.5±0.4
6.0	96.2±1.7	198.2±0.9
7.0	42.3±1.4	126.3±1.7
INCUBATION CONDITIONS: Inoculum size (cm): 1.5; Substrate: moistening agent: 1:3; Incubation period (days): 7 (TG) and 8 (TL); Incubation temperature (°C): 29±2. *STG$_D$: Dye adsorbed spent tea granules; STL$_D$: Dye adsorbed spent tea leaves *±: standard deviation from the mean		

3.3 Laccase production under optimized SSF conditions using tea waste and preparation of STG$_{FD}$ & STL$_{FD}$ (dye adsorbed spent tea biomass with spent fungal biomass) for 2nd cycle of adsorption-fermentation

The maximum laccase production by *P. chrysosporium* MTCC 787 with STG$_D$ and STL$_D$ as solid substrate was 89.2±1.7 U/mL at 29±2°C temperature, pH 6, inoculum size of 1.5 cm (6 fungal discs, each of the size, 0.25 cm) in 7 days of incubation. Similarly, for STL$_D$ as substrate, the optimal conditions for laccase production were same except, for incubation time required (8 days), but the laccase activity was almost double (180.1±2.1 U/mL) of obtained for STG$_D$ The spent dye adsorbed tea-fungal biomass left after enzyme production (STG$_{FD}$ & STL$_{FD}$) was collected and appropriately stored.

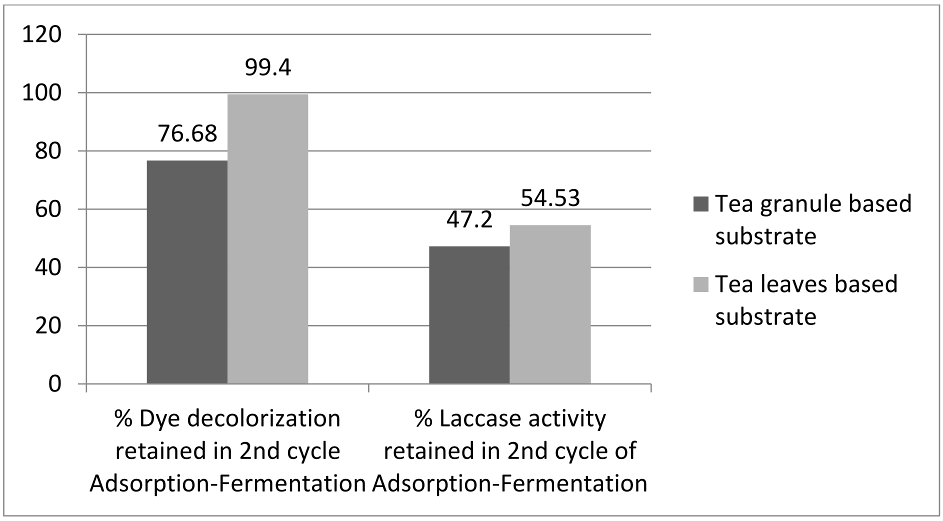
3.4 2nd cycle of adsorption-fermentation

The spent fungal-tea-biomass waste still yielded significant dye removal, with STG$_{FD}$ retaining more than 76% dye removing ability as compared to STG$_D$. Interestingly, STL$_{FD}$ exhibited comparable dye removal behavior in comparison to its control (STL$_D$) with around 99% dye decolorization ability still retained by the adsorbent. The laccase production was also reduced but was still economically valuable enzyme activity, with more than 45% activity retained by STG$_{FD}$ and STL$_{FD}$ retaining around 55% of the laccase activity (Table 3, Figure 2). Similar cyclic utilization of the organic waste for repeated use as adsorbent for methylene blue and enzyme substrate for laccase (Singh et al., 2022) indicated interesting observations where, wheat straw (by 4.9%) and rice husk-wheat straw (by 2.7%) showed enhanced dye adsorption in the 2nd cycle as compared to 1st cycle of adsorption-fermentation. The laccase production for both, though slightly decreased (as also observed in the current study) for wheat straw and rice husk-wheat straw. At the same time, rice husk showed slight decrease in dye adsorption in 2nd cycle than that for 1st cycle of adsorption-fermentation but laccase activity slightly increased.

Table 3: Comparative evaluation of tea waste as substrate in multiple cycles of Adsorption-Fermentation

Adsorption-Fermentation Cycle	Substrate	Dye Decolorization (%)	Laccase Production (U/mL)
1st	Tea granule waste based adsorbent/fermentation substrate (STG/STG_D)	91.3	89.2± 1.7
	Tea leaves waste based adsorbent/fermentation substrate (STL/STL_D)	92	180.1± 2.1
2nd	Tea granule waste based adsorbent/fermentation substrate (STG_{FD})	70	42.1± 0.7
	Tea leaves waste based adsorbent/fermentation substrate (STL_{FD})	91.4	98.2± 1.9
Adsorption conditions	Incubation temperature (° C): 70 (Tea granule waste) and 60 (Tea leaves waste)); Incubation time (minutes): 120; Dye concentration (mg/L): 10; pH : 7 (STG) and 8 (STL)		
Fermentation conditions	Incubation time, days: 7 (STG_{FD}), 8 (STL_{FD}); pH: 6; Temperature, °C: 29±2; Inoculum size, cm: 1.5 (6 fungal discs of 0.25 cm each)		
*±: standard deviation from the mean			

Figure 2: % Dye decolorization and Laccase activity retained in 2nd Adsorption-Fermentation cycle



Future Scope

Further investigations to check dye removal ability for various synthetic dyes especially, azo dyes, and potential reuse of such dye adsorbed substrates (which would otherwise be simply disposed of into the environment) for producing economically important products, without any potential health hazard, can go a long way in meeting Sustainable Development Goals (SDGs). Future investigations to understand the chemical behavior, detailed characterization and potential effect of modification of the tea waste for such uses, can help improvise the experimental quality of its use in such applications. The tea waste use for dye pollution can be better scaled up by improving its efficacy as adsorbent, which can be done by evaluating physical and chemical modifications of the tea waste for improved adsorptive properties. Pretreatment strategies for preventing leaching of tea organic matter like, tannins, in water would help in further using the tea waste for dye pollution mitigation.

Conclusion

The current study provides valuable insights to the potential use of tea waste as a dye adsorbent, and also a fermentation substrate for production of laccase, which is a commercially valuable enzyme. With promising (more than 90%) dye removal and laccase production (89.2 U/mL for STG and 180.1 for STL) ability, the tea waste, both in granule form as well as leaves form, offer promising dye adsorption as well as laccase production even in the 2nd adsorption-fermentation cycle. As tea waste is a wonderfully cheap, readily available natural material, its use generating commercially important products like, enzymes and in waste management help in transitioning from a linear to a circular economy.

References

Abbas, M.A., Abdulrazzak, F.H., Sabbar, W.J., Faraj, R.A.S., Adsorption of dyes by activated carbon surfaces were prepared from plant residues: Review. *Journal of Materials and Environmental Science*, *11(*12), 2007-2015.

Akar, E., Altinişik, A., Seki, Y. (2013) Using of activated carbon produced from spent tea leaves for the removal of malachite green from aqueous solution. *Ecological Engineering*, *52*, 19-27. https://doi.org/10.1016/j.ecoleng.2012.12.032.

Alzain, H.M., Kalimugogo, V., Hussein, K., Karkadan, M., A review of environmental impact of azo dyes, International Journal of Engineering Research and General Science, 10(6): 673-689. 10.52403/ijrr.20230682.

Asad, S., Amoozegar, M.A., Pourbabaee, A., Sarbolouki, M.N., Dastgheib, S. M.M. (2007) Decolorization of textile azo dyes by newly isolated halophilic and halotolerant bacteria. *Bioresource technology*, *98*(11), 2082-2088. https://doi.org/10.1016/j.biortech.2006.08.020.

Auta, M., Hameed, B. H. (2011) Preparation of waste tea activated carbon using potassium acetate as an activating agent for adsorption of Acid Blue 25 dye. *Chemical Engineering Journal*, *171*(2), 502-509. https://doi.org/10.1016/j.cej.2011.04.017.

Badawi, A.K., Elkodous, M.A., Ali, G.A.M. (2021) Recent advances in dye and metal ion removal using efficient adsorbents and novel nano-based materials: an overview, *RSC Advances*, *11*(58), 36528-36553. 10.1039/d1ra06892j.

Bansal, M., Patnala, P.K., Dugmore, T. (2020) Adsorption of Eriochrome Black-T (EBT) using a tea waste as a low cost adsorbent by batch studies: A green approach for dye effluent treatments. *Current Research in Green and Sustainable Chemistry*, *3*, 100036. https://doi.org/10.1016/j.crgsc.2020.100036.

Cakmak, T.G., Saricaoglu, B., Ozkan, G., Tomas, M., Capanoglu, E. (2024) Valorization of tea waste: Composition, bioactivity, extraction methods, and utilization, *Food Science & Nutrition*, *4*(12): 3112-3124. doi: 10.1002/fsn3.4011.

Das, S., DebSarkar, A., Singh, S. (2023) Designing and implementation of Internet of Things (IoT) on physico-biological treatment of wastewater. *Clean Soil, Air, Water*, 2300248, https://doi.org/10.1002/clen.202300248.

Das, S., Singh, S., Garg, S. (2019) Evaluation of Wheat Bran as a Biosorbent for Potential Mitigation of Dye Pollution in Industrial Wastewaters. *Oriental Journal of Chemistry*, *35*(5):1565-1573. http://dx.doi.org/10.13005/ojc/350514.

Dawood, S., Sen, T. K. (2012) Removal of anionic dye Congo red from aqueous solution by raw pine and acid-treated pine cone powder as adsorbent: equilibrium, thermodynamic, kinetics, mechanism and process design. *Water research*, *46*(6), 1933-1946. https://doi.org/10.1016/j.watres.2012.01.009.

Debnath, B., Haldar, D., Purkai, M.K. (2021) Potential and sustainable utilization of tea waste: A review on present status and future trends. Journal of Evironmental Chemical Engineering, https://doi.org/10.1016/j.jece.2021.106179.

Desai, S.S., Tennali, G.B., Channur, N., Anup, A.C., Deshpande, G., Murtuza, B.P. (2011) Isolation of laccase producing fungi and partial characterization of laccase, *Biotechnol. Bioinf. Bioeng*. *1*, 543-549. Corpus ID: 30770368.

El Maguana, Y., Elhadiri, N., Benchanaa, M., Chikri, R. (2020) Activated carbon for dyes removal: Modelling and Understanding the adsorption process, *Journal of Chemistry*, https://doi.org/10.1155/2020/2096834.

Elshafei, A.M., Hassan, M.M., Haroun, B.M., Elsayed, M. A., Othman, A.M. (2012) Optimization of laccase production from *Penicillium martensii* NRC 345. *Advances in life Sciences*, *2*(1), 31-37. DOI:10.5923/j.als.20120201.05.

Foroughi-Dahr, M., Abolghasemi, H., Esmaieli, M., Nazari, G., Rasem, B. (2015) Experimental study on the adsorptive behavior of Congo red in cationic surfactant-modified tea waste. *Process Safety and Environmental Protection*, *95*, 226-236. https://doi.org/10.1016/j.psep.2015.03.005.

Ghoreishi, S.M., Haghighi, R. (2003) Chemical catalytic reaction and biological oxidation for treatment of non-biodegradable textile effluent. *Chemical engineering journal*, *95*(1), 163-169. https://doi.org/10.1016/S1385-8947(03)00100-1.

Gochev, V.K., Krastanov, A.I. (2007) Isolation of laccase producing *Trichoderma* spp. *Bulgarian Journal of Agricultural Science*, *13*(2), 171.

Gomez, V., Larrechi, M. S., Callao, M. P. (2007) Kinetic and adsorption study of acid dye removal using activated carbon. *Chemosphere*, *69*(7), 1151-1158. https://doi.org/10.1016/j.chemosphere.2007.03.076.

Guo, S., Awasthi, M.K., Wang, Y., Xu, P. (2021) Current understanding in conversion and application of tea waste biomass: A review. *Bioresource Technology*, 338, 125530. https://doi.org/10.1016/j.biortech.2021.125530.

Gupta, V.K. (2009) Application of low-cost adsorbents for dye removal–A review. *Journal of environmental management*, *90*(8), 2313-2342. https://doi.org/10.1016/j.jenvman.2008.11.017.

Gupta, V.K., Kumar, R., Nayak, A., Saleh, T. A., Barakat, M.A. (2013) Adsorptive removal of dyes from aqueous solution onto carbon nanotubes: a review. *Advances in colloid and interface science*, *193*, 24-34. https://doi.org/10.1016/j.cis.2013.03.003.

Gupte, A., Gupte, S., Patel, H. (2007) Ligninolytic enzyme production under solid state fermentation by white rot fungi. *Journal of scientific and industrial research*, *66*(8), 611.

Hussain, S., Anjali, K. P., Hassan, S. T., & Dwivedi, P. B. (2018). Waste tea as a novel adsorbent: A review. Applied Water Science, 8(6), 1–16. https://doi.org/10.1007/s13201-018-0824-5.

Irshad, M., Asgher, M., Sheikh, M. A., & Nawaz, H. (2011) Purification and characterization of laccase produced by *Schyzophylum commune* IBL-06 in solid state culture of banana stalks. *BioResources*, *6*(3), 2861-2873. DOI: 10.15376/biores.6.3.2861-2873.

Ivanka, S., Albert, K., Veselin, S. (2010) Properties of crude laccase from *Trametes versicolor* produced by solid-substrate fermentation. *Advances in Bioscience and Biotechnology*, *1*(3). doi: 10.4236/abb.2010.13029.

Jafari, A., Aaghebati, S., Khayati, G. (2023) Decolorization of azo dyes by produced laccase enzyme in solid-state fermentation using biphenyl as an inducer, Biocatalysis and Agricultural Biotechnology, 52, 102814. https://doi.org/10.1016/j.bcab.2023.102814.

Kalme, S.D., Parshetti, G.K., Jadhav, S.U., Govindwar, S. P. (2007) Biodegradation of benzidine based dye Direct Blue-6 by Pseudomonas desmolyticum NCIM 2112. *Bioresource Technology*, *98*(7), 1405-1410. https://doi.org/10.1016/j.biortech.2006.05.023.

Khosla, E., Kaur, S., Dave, P.N. (2011) Surfactant modified tea waste as a novel adsorbent for the removal of Basic dye. *Der Chem. Sinica*, 87–102.

Kumar, S.S., Balasubramanian, P., Swaminathan, G. (2013) Degradation potential of free and immobilized cells of white rot fungus Phanerochaete chrysosporium on synthetic dyes. *International Journal of ChemTech Research*, *5*(2), 565-571.

Lellis, B., Fàvaro-Polanio, C.Z., Pamphile, J.A., Polonio, J.C. (2019) Effects of textile dyes on health and the environment and bioremediation potential of living organisms, *Biotechnology Research and Innovation*, *3* (2), 275-290. https://doi.org/10.1016/j.biori.2019.09.001.

Lima, U.S., Malangi, S., Ali, M.K., Suhag, M.H., Kayes, M.N. (2024) Spent tea leaves as an adsorbent material: preparation, characterization, and application. IOSR Journal of Applied Chemistry, 17(10), 27-34. 10.9790/5736-1710012734.

Molinari, R., Pirillo, F., Falco, M., Loddo, V., Palmisano, L. (2004) Photocatalytic degradation of dyes by using a membrane reactor. *Chemical Engineering and Processing: Process Intensification*, *43*(9), 1103-1114. https://doi.org/10.1016/j.cep.2004.01.008.

Muthezhilan, R., Ashok, R., Jayalakshmi, S. (2007) Production and optimization of thermostable alkaline xylanase by Penicillium oxalicum in solid state fermentation. *African Journal of Microbiology Research*, *1*(2), 20-28.

Nakamura, T., Mishima, S., Ogata, F., Kawasaki, N. (2022) Characteristics of 21 Types of Tea waste for adsorbance of ionic dyes from aqueous solutions, Chemical and Pharmacueitcal Bulletin, 70(4), 254-260. https://doi.org/10.1248/cpb.c21-00973.

Nandal, P., Ravella, S. R., Kuhad, R. C. (2013) Laccase production by *Coriolopsis caperata* RCK2011: optimization under solid state fermentation by Taguchi DOE methodology. *Scientific reports*, *3*. 1386. https://doi.org/10.1038/srep01386.

Ozmen, N., Yesilada, O. (2012) Valorization and biodecolorization of dye adsorbed on lignocellulosics using white rot fungi. *BioResources*, *7*(2), 1656-1665. DOI: 10.15376/biores.7.2.1656-1665.

Pang, Y.L., Abdullah, A.Z. (2013) Current status of textile industry wastewater management and research progress in Malaysia: a review. *Clean–Soil, Air, Water*, *41*(8), 751-764.https://doi.org/10.1002/clen.201000318.

Pirbazari, A.E., Saberikhah, E., Badrouh, M., Emami, M.S. (2014) Alkali treated Foumanat tea waste as an efficient adsorbent for methylene blue adsorption from aqueous solution. *Water Resources and Industry*, *6*, 64-80. https://doi.org/10.1016/j.wri.2014.07.003.

Rafatullah, M., Sulaiman, O., Hashim, R., Ahmad, A. (2010) Adsorption of methylene blue on low-cost adsorbents: a review. *Journal of hazardous materials*, *177*(1-3), 70-80. https://doi.org/10.1016/j.jhazmat.2009.12.047.

Richter, D.L., Kangas, L.C., Smith, J.K., Laks, P.E. (2010) Comparison of effectiveness of wood decay fungi maintained by annual subculture on agar and stored in sterile water for 18 years. *Canadian journal of microbiology*, *56*(3), 268-271. https://doi.org/10.1139/W10-001.

Singh, S., Tyagi, C.H., Dutt, D., Upadhyaya, J.S. (2009) Production of high level of cellulase-poor xylanases by wild strains of white rot fungus *Coprinellus disseminatus* in solid state fermentation, *New Biotechnology*, *26(¾),*165-170. https://doi.org/10.1016/j.nbt.2009.09.004.

Singh, S., Adeyemi, K.T., Vernwal S., (2022) Adsorption-microbial fermentation based multi-step approach to dye remediation for safe and environment compatible waste water treatment, *Environmental Challenges*, 100459. https://doi.org/10.1016/j.envc.2022.100459.

Sugumaran, P., Susan, V.P., Ravichandran, P., Seshadri, S. (2012) Production and characterization of

activated carbon from banana empty fruit bunch and Delonix regia fruit pod. *Journal of Sustainable Energy & Environment*, *3*(3), 125-132.
Das, S., Singh, S., Garg, S. (2021) Agri-residual waste, wheat bran as a biosorbent for mitigation of dye pollution in industrial wastewaters. *Journal of Basic Microbiology*, *62* (3-4). 465-479. https://doi.org/10.1002/jobm.202100502.
Tan, L., Ning, S., Zhang, X., Shi, S. (2013) Aerobic decolorization and degradation of azo dyes by growing cells of a newly isolated yeast Candida tropicalis TL-F1. *Bioresource technology*, *138*, 307-313. https://doi.org/10.1016/j.biortech.2013.03.183.
Tea board of India, https://www.teaboard.gov.in/.
Tea market worldwide, https://www.statista.com/topics/6922/tea-market-worldwide/#topicOverview. Accessed on 2nd August 2025.
Tekere, M., Mswaka, A.Y., Zvauya, R., Read, J. S. (2001) Growth, dye degradation and ligninolytic activity studies on Zimbabwean white rot fungi. *Enzyme and Microbial Technology*, *28*(4), 420-426. https://doi.org/10.1016/S0141-0229(00)00343-4.
Uddin, M. T., Islam, M. A., Mahmud, S., Rukanuzzaman, M. (2009) Adsorptive removal of methylene blue by tea waste. *Journal of Hazardous Materials*, *164*(1), 53-60. https://doi.org/10.1016/j.jhazmat.2008.07.131.
Unuabonah, E.I., Adie, G.U., Onah, L. O., Adeyemi, O.G. (2009) Multi-stage optimization of the adsorption of methylene blue dye onto defatted Carica papaya seeds. *Chemical Engineering Journal*, *155*(3), 567-579.
Vithalkar, S. and Jugade, R. (2023) A promising low cost adsorbent based on tea-waste for confiscation of crystal violet dye, Indian Journal of Engineering and Materials Sciences, 30(6) https://doi.org/10.56042/ijems.v30i6.4521.
Wong, S., Ghafar, N.A., Ngadi, N. Razmi, F.A., Inuwa, I.M., Mat, R., Amin, N.A.S. (2020) Effective removal of anionic textile dyes using adsorbent synthesized from coffee waste. *Sci Rep 10*, 2928. https://doi.org/10.1038/s41598-020-60021-6.
Xu, L., Sun, K., Wang, F., Zhao, L., Hu, J., Ma, H., Ding, Z. (2020) Laccase production by Trametes versicolor in solid-fermentation using tea residues as substrate and its application in dye decolorization, *Journal of Environmental Management*, *270*, 110904. https://doi.org/10.1016/j.jenvman.2020.110904.
Yagub M.T., Sen T.K., Afroze S., Ang H.M. (2014) Dye and its removal from aqueous solution by adsorption: a review. *Adv. Colloid Interface Sci.*., *209*, 172-184. https://doi.org/10.1016/j.cis.2014.04.002.
Yagub M.T., Sen T.K., Ang H.M. (2012) Equilibrium, kinetics, and thermodynamics of methylene blue adsorption by pine tree leaves. *Water Air Soil Pollut.*. *223*, 5267-5282. https://doi.org/10.1007/s11270-012-1277-3.

Ethanolic extract of waste spinach leaves for corrosion prevention of copper in 3.5 % NaCl

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ABSTRACT

Corrosion is the natural deterioration of the metals due to their high and imbalanced energy. The corrosion causes significant loss of metals, which can lead to failure generating economic losses and safety threats for human. One of the most effectual approaches for corrosion control is coating of protective materials on metal surfaces. The coating isolates metals from surroundings and protects the base metal. Though inorganic coating materials can be used for the above-mentioned purpose, organic materials are preferred for corrosion protection due to their sustainability, effectiveness, low-cost, low to negligible toxicity, and easy availability. Organic materials derived from natural sources are good alternatives for the same. One of the similar organic materials (spinach leaves) has been investigated in this work for copper's (Cu) prevention in 3.5wt% NaCl solution. The waste spinach leaves (SL) obtained from house garbage have been extracted in ethanol and tested by spectroscopic techniques. The ethanol extract of spinach leaves (EESL) is found rich in biomolecules, which is good for its stacking strength on Cu. The EESL has been deposited on Cu by drop casting (DC) in layers (1-3). The coated Cu samples have been examined by open circuit potential (OCP), Tafel polarization curves (TPC), electrochemical impedance spectroscopy (EIS), and optical microscopy (OM). The corrosion tests (OCP, EIS, and TPC) have shown that EESL coatings effectively protect Cu in NaCl. It is noticed that the maximum corrosion protection (85%) has been offered by 3 layers of EESL-coated Cu. It has been analyzed that the efficient coverage of Cu surface by nobler EESL layers are responsible for this. This fact has also been disclosed by OM studies of Cu surfaces. Based on overall examination, a schematic corrosion protection mechanism has also been made and discussed. Future scope of the work is performing tests at industrial scale, purification of the extract, and experiments in different environmental conditions.

Keywords: Copper; Corrosion; NaCl; Spinach Leaves; Coating; EIS.

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1. Introduction

Metals are widely used in many industrial applications as well as domestic appliances. It is necessary for their prolonged life that they must be prevented from possible attacks. One of the most severe attacks on metals during their exposure is corrosion. The Corrosion is termed as the static degradation of metals due to their interaction with the exposure media to balance their surplus energy (Bender et al., 2022). Due to corrosion, metals start to go in their natural form (ore), which is not useful for engineering applications. The process of corrosion is gradual, natural, and uncontrolled. The issues with metal corrosion can lead to large financial losses, environmental damage, and possible hidden risks to our lives (Abuelela et al, 2023). Therefore, effective metal corrosion prevention has always been the primary goal of interested researchers. There are many methods available for corrosion prevention; however, coatings can be employed as one of the easiest and effective methods to control corrosion (Chhipa et al., 2024, Li et al., 2025). The inorganic coating materials are very effective against corrosion (Xue et al., 2025, Yang, 2025); however, they pose a significant risk due to their toxicity. Hence, their use is discouraged. Instead of using them, organic compounds from natural materials (NMs) can be used to control corrosion (Sun et al., 2023). They are also efficient as synthetic coating materials (Pandey et al., 2025). They are economic and eco-friendly, too. Hence, they can be preferred to be used over inorganic coating materials due to strict environmental regulations.

NMs like fruits, plants, and vegetables are considered significant sources of organic compounds that are widely available, renewable, and environmentally acceptable (Umoren et al., 2013, Li et al., 2025). Organic compounds from NMs can be obtained by simple extraction techniques using suitable solvents (Ji et al., 2024, Pal et al., 2020, Shekhar et al., 2021). Hence, it is a wise decision to use them in corrosion prevention applications. In this regard, waste of NMs can also be used for corrosion prevention of metals. In daily life, many of such NMs are discarded by individuals and Agro-products manufacturing companies. The waste and discarded materials still contain many natural compounds and can show high corrosion prevention properties. For example, banana peels (Ji et al., 2021), lady finger caps (Pandey et al., 2025), and watermelon seeds (Jaiswal et al., 2025) are waste NMs and show high corrosion prevention abilities. On the other side, these wastes can spread diseases and pollute soil after rotting and improper disposal (Jaiswal et al., 2025). The rotten wastes could attract different harmful bacteria, insects, and similar species to grow, which can generate diseases. Also, these wastes could generate harmful byproducts after rooting and get mixed in the soil for polluting it. Hence, it is a logical decision to use them for corrosion control applications. A similar kind of waste NMs (Spinach leaves) has been used in this work. Due to bad appearance and health factors (Xu et al., 2024), all spinach leaves (SL) are not directly used in home and packaged food in market. Some of the leaves has been discarded due to above mentioned reasons and becomes an unwanted byproduct of market and domestic waste. Only the discarded leaves (waste) in the study was used for preventing Cu in 3.5 wt% NaCl. The Cu has been selected for the investigation because copper is commercially used in many domestic and industrial appliances for its high electrical and thermal conductivity, and anti-microbial properties (Jafari et al., 2016, Zdravković et al., 2023).

The aims of the research in this work are to extract SL in ethanol, deposit EESL on Cu by drop casting (DC), and to examine corrosion behaviors of EESL-coated Cu samples in 3.5 wt% NaCl. The spinach is famous as 'palak' in India and consumed for iron supplements. The botanical name of spinach is Spinacia oleracia. It belongs to Amarantheceae family. The SL (Figure 1) is considered as a good source of minerals, vitamins, flavonoids, alkaloids, and ascorbic acids (Kumar and Singh, 2019, Faujan et al, 2023). The flavonoids, alkaloids, and ascorbic acids are well known organic compounds for excellent corrosion controlling properties (Sithuba et al. 2022, Thakur et al., 2020). Due to novelty of Spinach, it has already been employed as corrosion inhibitors by researchers. Shivakumar et al. (Shivakumar et al., 2013) have reported the maximum inhibition efficiency of spinach leaves extract for mild steel in 0.5 M HCl as 86% using 2000 ppm of the extract. Liu et al. (Liu et al., 2023) have reported the maximum inhibition efficiency of spinach extract for Q235 steel in 0.5 M HCl as >90% using 300 ppm of the extract. Hameed et al. (Hameed et al., 2022) have reported the maximum efficiency of 93.2% for carbon steel in 1 M HCl using 500 ppm of the extract. In addition, SLs are also used for medical purposes. All above mentioned factors motivated us to use SL for corrosion examination in our work. One of most important and novel factors behind using SL in this work is that it is used only as inhibitors for other metals in previously published works and never used as a coating material for corrosion prevention of Cu. Hence, EESL is used in this work to examine its anti-corrosive properties for Cu in 3.5 wt% NaCl. DC is selected as a coating method in this work because it is one of the easiest, the most economic, and the quickest methods to develop films on substrates (Wang et al., 2016, Jia et al., 2018). The ethanol has been used for extraction because it is volatile, can extract compounds that do not dissolve easily in water (ideal for coating applications), safe to use, and stable for a long time at the room temperature (Hassim et al., 2021). The examination has been done by OCP, EIS, TPC, OM, and spectroscopic techniques. The investigation has declared that EESL can be successfully utilized as a coating material for prventing Cu in 3.5wt% NaCl.

Figure 1. Showing the image of Spinach leaf. Adapted from Kumar and Singh (Kumar et al., 2019). No permission required (Open Access).

2. Experimental Details

2.1 Extraction

The EESL has been prepared as per the method given in Pandey et al. (Pandey et al., 2025). Waste green SLs from a nearby home's kitchen waste were gathered. After being carefully cleaned with distilled water, the SLs were patted dry using tissue paper. After removing the petioles, the SLs were dried in an electric oven set 50° C for three hours. A household kitchen grinder (750 W) was used to grind the dried SLs to make it powdered. For one day, the resulting powder was agitated at 400 rpm while soaking 5 gm of SL in 50 mL of ethanol (Fisher, AR Grade, 99.9%). Following the extraction time, Whatman filter paper (Grade 1) was used to purify the mixture. The majority of the powder (3 gm) was dissolved in ethanol, while an amount equal to 2 gm was recollected as residues. The yield of the extraction process was 60%. Thus obtained EESL was used in the all experiments. The extraction process has been schematically displayed in Figure 2.

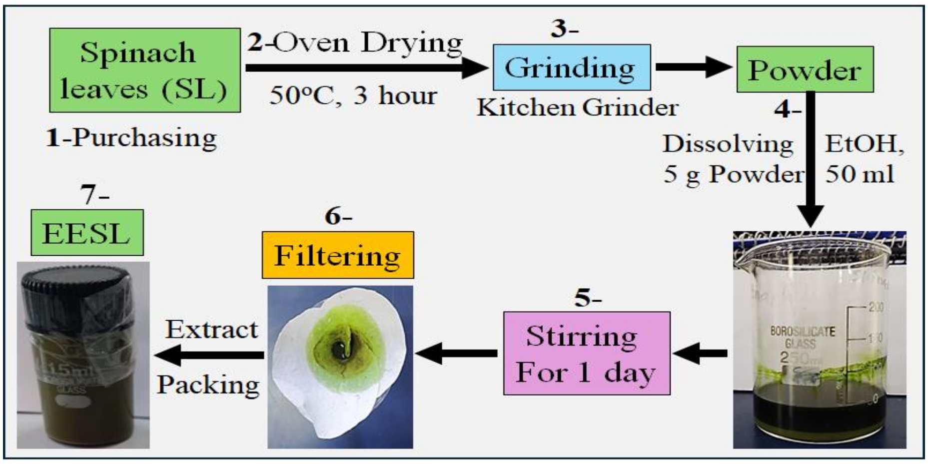

Figure 2. Schematic illustration of the spinach leaves extract preparation.

2.2 Testing EESL

Using a Biotek spectrophotometer and a Thermo Scientific Nicolet 6700 (FTIR), the extract was analyzed for the presence of biomolecules. A 200 µL sample of EESL was analyzed in the UV-Visible range of 200-900 nm and the FTIR range of 400-4000cm^{-1}. The obtained spectra were analyzed to predict the biocompounds in the extract.

2.3 Cu specimen

A long roll of Cu sheet was purchased from United Industries, India. The roll was cut to make strips of dimension 4 cm × 1 cm × 0.02 cm. The strips had been cleaned with ethanol and compressed air after being ground on emery paper of Sianor B (Swiss). The strips were covered by a paint to create an area of only 1×1 cm^2 (front-bottom area) for electrochemical studies. For all the corrosion tests, these masked strips served as specimens.

2.4 EESL coating on Cu

The procedure given in Pandey et al. (Pandey et al., 2025) was adopted to drop cast EESL on Cu. A 40 µL of EESL was taken in a micropipette (volume range: 0-100 µL) and drop cast on Cu. After wait time of 20 minutes since drop cast, a layer of EESL had been created on Cu, after evaporation of ethanol. Thus, one layer of EESL was cast on Cu. The second layer was drop cast on one layer-coated Cu in a similar manner. Three EESL layers were thereby produced on Cu and put to the test in corrosion testing.

2.5 Electrochemical measurements

The electrochemical tests, including OPC, EIS, and TPC, were carried out on the CHI 7041 electrochemical workstation. The tests used an Ag/AgCl electrode as reference (RE), a platinum wire mesh as a counter electrode (CE), and Cu specimen as working electrodes (WE). The set up for performing the tests is shown in Figure 3. The strips underwent their first electrochemical test, which was OCP monitoring for 300 seconds. The short time of measurement was selected just to obtain a trend. However, further electrochemical measurements were performed after 1 hour of immersion. After wait period, EIS was performed using an a.c. current of 0.005V (RMS) in the 100000-0.01 Hz range. The Tafel test was performed in a potential window of 0.5 V with regard to the electrodes' OCP at 0.003 V s^{-1}. The impedance behaviors recorded from EIS and polarization behaviors obtained from TPC were examined o predict the corrosion behaviors of EESL-coated Cu in NaCl.

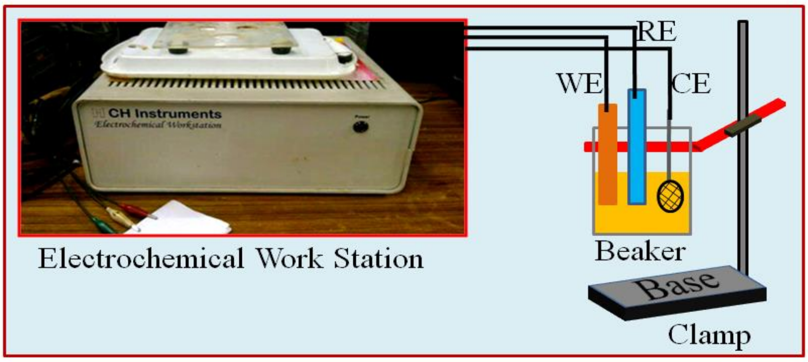

Figure 3. Showing **s**et-up used for performing the electrochemical experiments.

2.6 Surface Analysis

The polished Cu samples were incised into 1 (length) × 1 (width) cm^2 samples and dipped in 50 ml of 3.5 wt% NaCl without and with the optimum number of coating layer of EESL for 6 hours. The 3.5 wt% NaCl solution was selected as corrosive medium to mimic sea environment. The Cu samples were withdrawn after 6 hours, washed with distilled water, and demoisturized at 40°C in an oven for 15 minutes. The effects of immersion in NaCl alone and NaCl with EESL were easily observed by an optical microscope from Olympus and compared.

3. Results and Discussion

3.1 Synthesis of EESL

The UV-Visible spectrum (UVS) of EESL is shown in Figure 4. Several adsorption peaks could be easily observed in the spectrum, which showed interactions of organic compounds in the extract with UV-visible rays. A peak at 660 nm could indicate the substantial presence of chlorophyll (green color). The peaks at 444 nm and 537 nm could indicate n-π* transitions in the extract's compounds. The peak at 280nm could correspond to flavonoids (aromatic compounds) in the extract (Mikheev and Ershov, 2018).

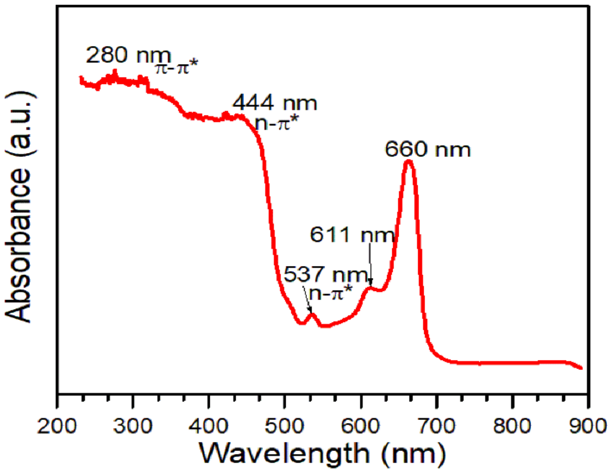

Figure 4. UV-Visible spectrum of the synthesized EESL.

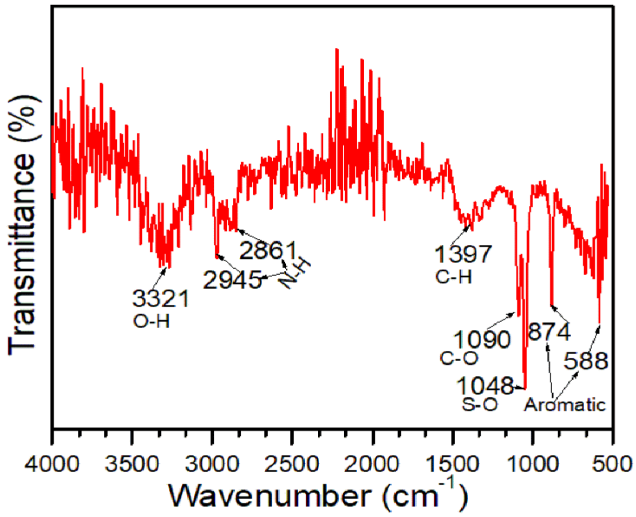

Figure 5. FTIR spectrum of the synthesized EESL.

The FTIR spectrum of EESL is illustrated in Figure 5. The peak at 3321 cm^{-1} could show presence of O-H functional group form ethanol and ascorbic acid. The peaks at 2861 cm^{-1} and 2945 cm^{-1} could point out N-H functional groups from alkaloids. The peaks at 1397 cm^{-1} and 1090 cm^{-1} could show presence of C-H and C-O functional groups from ascorbic acid and flavonoids. The peak at 1048 cm^{-1} could represent S-O functional group. The peaks at 874 cm^{-1} and 588 cm^{-1} could correspond to flavonoids in the extract. The SLs have been reported to be rich in minerals, vitamins, flavonoids, alkaloids, and ascorbic acids (Kumar and Singh, 2019, Faujan et al, 2023). This fact was also verified by the results obtained this work through UVS and FTIR spectra.

3.2 Electrochemical corrosion measurements

Figure 6 depicts the fluctuation in OCPs of 1 layer, 2 layers, 3 layers EESL coated Cu substrates over 300 seconds. The bare Cu showed the highest negative potential than potential of coated Cu samples. Also, it was observed that OCPs shifted towards positive potentials relative to OCP of bare Cu. This could mean that EESL coatings were preventing Cu in NaCl (Leslie and Mauzeroll, 2024). This observation also suggested that Cu coated with 3 layers of EESL could perform better than other samples against corrosion (Tiwari et al., 2018). Though OCPs alone could not be used to predict the corrosion tendency, it provided the basic idea about the EESL properties. Further properties could be known through EIS and TPCs study.

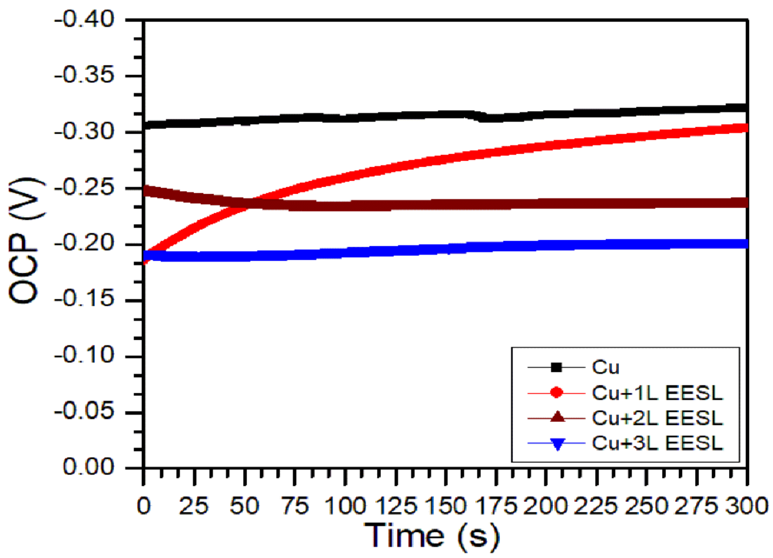

Figure 6. OCPs for Cu substrates in 3.5 wt% NaCl at room temperature (25±2°C) for 300 seconds.

The first confirmatory test that was used to comment on corrosion properties of EESL was EIS. EIS tests were conducted at the end OCP voltages. Figure 7 displays the (a) Nyquist and (b) Bode phase plots for bare and coated Cu samples. The first information after seeing the Nyquist plots was obtained that they were in semicircular form, which indicated that only charge transfer reactions were occurring at the surfaces of Cu samples (Arenas et al., 2004). It was additionally observed that semi-circular shapes of the Nyquist plots were not perfect and looked like depressed under X-axis of the plot. This information could suggest that coatings did not cover the surfaces of Cu uniformly. It matches with the fact that drop casting method suffers from uniformity and irregularity of the layers deposited (Semwal et al., 2025). Also, drop cast method suffers with the scaling-up process. Hence, it is best suited for lab-scale experiments to know the preliminary idea about the corrosion prevention. Furthermore, it was observed that the diameters of Nyquist plots augmented with the number of EESL layers. The diameter of a Nyquist plot usually corresponds to impedance of the investigated system (Pandey et al., 2019). Any augmentation in diameter indicates that impedance of the system has increased. This fact could suggest that EESL layers prevented corrosion of Cu in NaCl because the lowest diameter of Nyquist plot was noticed for bare Cu. The biggest diameter of the Nyquist plot was noticed for 3 layers EESL-coated Cu. This fact could suggest that 3 layers of EESL were the most protective formulation for Cu in comparison to other coated samples. For further investigation, the Bode phase plots are shown in Figure 7b. It was observed that the highest phase angle was acknowledged for 3 layers coated EESL. This could simply indicate that the highest degree of protection to Cu was supplied by 3 layers of EESL (Lou and Singh, 2011). It could also indicate that process was one time constant process (Ji et al., 2024). The reason of increased impedance of coated Cu samples based on Nyquist and Bode phase plots could be predicted as coverage of Cu surface by EESL layers (Maurya et al., 2024). This could also disclose that the highest surface was provided by 3 layers of EESL coatings.

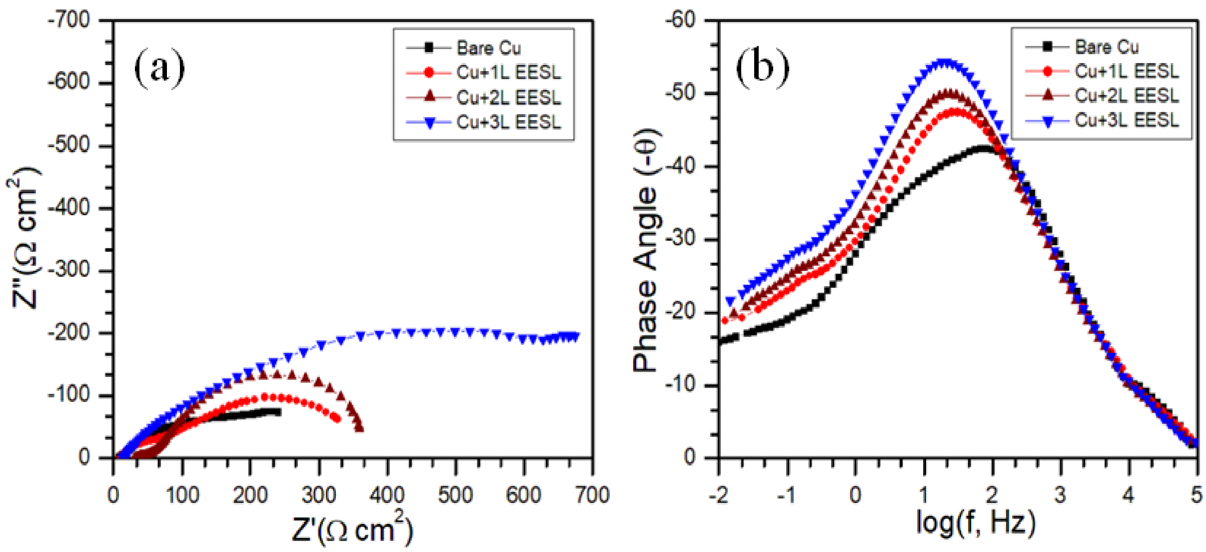

Figure 7. (a) Nyquist and (b) Bode phase curves of Cu and EESL coated Cu in 3.5 wt% NaCl at room temperature.

Figure 8 depicts Tafel polarization curves (TPCs) for bare and EESL-coated Cu samples. Initial research of TPCs indicated that they moved towards the lesser current areas and positive potential areas. This raw information showed that EESL layers were protective in nature and nobler than bare Cu (Jaiswal et al., 2023). Since EESL layers were nobler than Cu, they could act as a physical barrier against corrosion (Stern and Geary, 1957) and stop corrosive species. Furthermore, it was discovered that the changes in anodic polarization curves were more visible than that the changes in cathodic polarization curves, which could imply that EESL was more prominently preventing anodic corrosion reactions (Cu dissolution in NaCl) than cathodic corrosion reactions (Lavanya et al., 2023). However, more information on this could only be known through extrapolation of the curves.

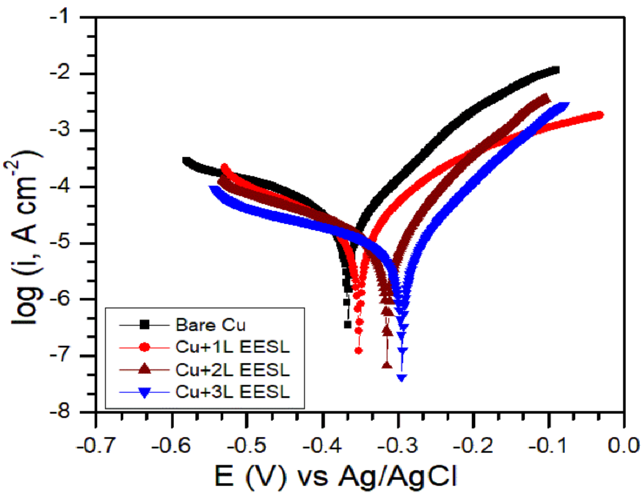

Figure 8. Tafel polarization curves for bare and EESL coated Cu in 3.5 wt% NaCl at room temperature.

To extract more details, the TPCs were extrapolated and corrosion current density (I_{corr}) along with equilibrium corrosion potential (E_{corr}) were estimated. Also, the corrosion prevention efficiencies (μ_p) had been calculated from the formula given below (Li et al., 2023):

$$\mu_p(\%) = \frac{I^{o}_{corr} - I^{p}_{corr}}{I^{o}_{corr}} \times 100 \qquad \text{(i)}$$

Where, superscripts "o" and 'p' shows I_{corr} values for bare and coated Cu samples in pure NaCl, respectively.

The parameters from the TPCs have been calculated and shown in Table 1. The bare Cu showed E_{corr} value of -362 mV. The 1 layer EESL coated Cu, 2 layers EESL coated Cu, and 3 layers EESL coated Cu showed the E_{corr} values of -354 mV, -312 mV, and -286 mV, respectively. This fact disclosed that EESL made Cu nobler than bare Cu (Sohail et al., 2021), which was already disclosed by OCP analysis. Also, the maximum shift in E_{corr} values of coated Cu samples with respect to bare Cu was more than 85 mV and observed for 3 layers EESL coated Cu. This could simply show that 3 layers of EESL coatings mainly worked on prevention of Cu dissolution in NaCl (Rao et al., 2024). Furthermore, the I_{corr} for bare Cu was noticed as 41 µA cm^{-2}. It was observed that coated Cu showed lower I_{corr} values. These facts indicated that EESL coating lower the corrosion rate of Cu in 3.5 wt% NaCl because the I_{corr} value directly represents the corrosion rate for a system for comparison (Sharma and Ji 2023). The lowest I_{corr} value of 6 µA cm^{-2} was shown by 3 layers EESL coated Cu, which suggested that 3 layer EESL was the best in protection among others. The reason of prevention based on TPCs could be given as the EESL layers roofed the surfaces of Cu after deposition through drop casting and act as a physical barrier against corrosion. This was also reflected in the increasing anodic and cathodic Tafel slope ($ß_a$ and $ß_c$) values.Due to restriction in access of Cu by NaCl molecules, the response of Cu to sweeping voltage was restricted by EESL layers and the prevention had been achieved.

Table 1: The technical parameters of corrosion extracted from Tafel polarization curves for bare and EESL coated Cu in 3.5 wt% NaCl at room temperature.

S. No	Systems	-E_{corr} (mV)	I_{corr} (µA cm^{-2})	$ß_a$ (mV dec^{-1})	-$ß_c$ (mV dec^{-1})	$µ_p$ (%)
1	Bare Cu	362	41	209	187	-
2	Cu + 1 Layer EESL	354	20	242	196	51
3	Cu + 2 Layer EESL	312	12	273	206	70
4	Cu + 3 Layer EESL	286	6	316	232	85

3.3 Surface images

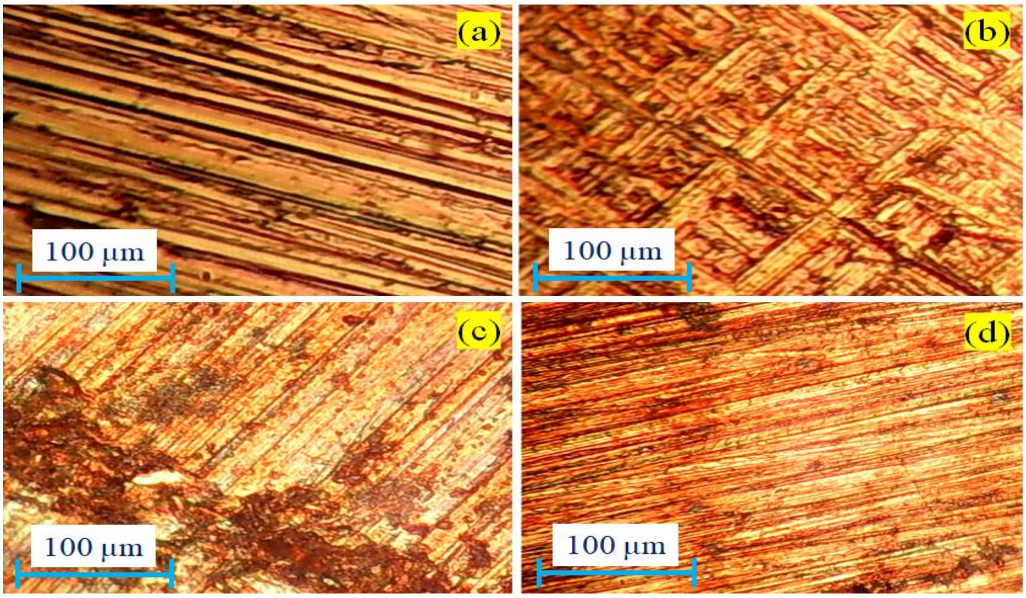

Figure 9. Optical microscope images of (a) bare Cu, (b) coated Cu, (iii) Corroded Cu (bare) and (iv) corroded Cu (EESL-coated).

The surface images are the best markers to judge the protection efficacy in a qualitative manner. The surface images could show the degree the protection offered by the corrosion prevention methods (Rai and Ji, 2023). The images of Cu surfaces in different conditions are shown in Figure 9. The scratch marks along with some pits on the surface of polished Cu could be visualized in Figure 9a, which could suggest that the surface was not uniformly polished. However, any evidence of external contamination was not seen on the surface. The surface of 3 layers EESL-coated Cu is shown in Figure 9b. On comparison with Figure 9a, it could be said that EESL effectually covered the Cu surface. However, the coating layer was looking irregular at some places, which could indicate that the deposition of EESL over Cu was not uniform. The surface of corroded Cu (bare) in NaCl is shown in Figure 9c. A large and rough pit on the surface could be easily visualized, which could indicate that corrosion of Cu was severely attacked by NaCl. The surface of corroded Cu (EESL-coated) is shown in Figure 9d. On comparison with Figure 9c, it could be evidently observed that EESL effectively prevented the corrosion of Cu in NaCl. The coating covered the Cu's surface and acted as physical barrier against NaCl. As a result, only limited areas on the surface was corroded by NaCl through some possible micro-channels.

3.4 Possible reasons for corrosion prevention

Coatings provide protection to underneath substrate in either sacrificial mode or barrier mode (Baisnab et al., 2021). The noble materials of coatings act as a barrier for base metal, whereas reactive materials provide protection in sacrificial mode. The tin coated iron is an example of barrier mode of protection, whereas zinc coated iron is an example of sacrificial mode of protection (Pandey et al., 2023, Makisha and Chukhin, 2023). The OCPs and E_{corr}s of EESL-coated Cu samples were more positive than bare Cu, which indicated that EESL-coated Cu samples were nobler than bare Cu. It also meant that EESL had provided protection to Cu in barrier mode.

After knowing that EESL coatings functioned in barrier mode, it was easy to predict the corrosion prevention mechanism. The first layer of EESL roofed the surface of bare Cu and prevented the corrosion to occur at covered surfaces. However, 1st layer of EESL was not enough to cover the whole surface and some areas remained uncovered. Hence, corrosion of the uncovered regions could occur. The 2nd layer of EESL could cover more areas on the surface and provide greater protection to Cu. The 3rd layer could cover more area on the surface than 2nd layer and could provide greater protection than 2nd layer. This fact was also found true in EIS and TPC results. The corrosion prevention efficiency was noticed to be augmented with the layers. The above mentioned fact was also mentioned elsewhere (Hsieh et al., 2024).

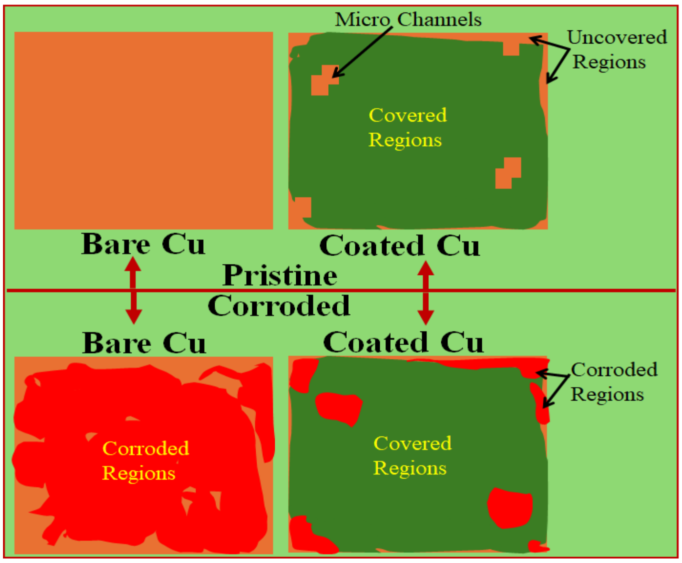

Figure 10. A schematic illustration of corrosion prevention of Cu by EESL coatings.

Based on above mentioned facts, a graphical illustration of corrosion prevention of Cu by EESL layers are shown in Figure 10. Bare Cu had large open area. NaCl could damage the surface severely and make heavy loss of Cu in solutions. In opposite, low damage of the surface occurred due to NaCl attack because coated Cu was covered and protected by EESL layers. However, some of the regions were not covered by EESL and had pores (micro channels) on the surface. The NaCl accessed Cu through these micro-channels and corroded its surface. Hence, the maximum prevention efficiency of 85% was achieved instead of 100%. The results for 4th layer of EESL were not presented here because no significant increase in the prevention efficiency was acknowledged. It might be because of saturation in coverage of Cu surface due to availability of more number of micro-channels for NaCl. The similar facts were reported elsewhere (Pandey et al., 2025, Eslamian and Soltani-Kordshuli, 2018, Alimohammadi et al, 2023).

4. Conclusion

This study determines the efficacy of a common household waste product (spinach leaves) as a green anti-corrosive material for Cu in 3.5 wt% NaCl. The various tests were conducted and results could be summarized as given below:

1. The EESL was found rich in flavonoids, ascorbic acids, and alkaloids as disclosed by spectroscopic techniques.
2. The OCPs of EESL-coated Cu revealed that coated Cu samples were nobler that bare Cu in NaCl. The most positive OCP was acknowledged for 3 layers EESL-coated Cu.
3. The impedance against corrosion was higher for coated Cu samples than bare Cu. The highest impedance was acknowledged for 3 layers EESL-coated Cu.
4. The E_{corr}s of EESL-coated Cu samples were greated than Cu, which revealed the same fact as disclosed by OCPs. The highest E_{corr} was recognized for 3 layers EESL-coated Cu.
5. The I_{corr}s of EESL-coated Cu was lower than bare Cu, which indicated that EESL coatings prevented corrosion of Cu in NaCl. The lowest I_{corr} had been attained with 3 layers EESL-coated Cu
6. Based on corrosion prevention efficiency, the samples can be ranked as: 3 layers EESL coated-Cu (85%)>2 layers EESL coated-Cu (70%)>1 layer EESL coated-Cu (51%) >bare Cu.
7. The reason of protection was revealed as coverage of Cu's surface by EESL layers that acted as a physical barrier against its corrosion in NaCl.
8. It is proposed based on the results of the work that incorporating spinach-based coatings into commercial corrosion protection systems in saline medium has the potential to drastically reduce both environmental pollution and economic costs associated with corrosion, providing the way for more sustainable materials.
9. Hence, the significant contributions of this study are addition of values to the valorization of agro-waste and domestic waste, sustainability and environmental safety, economic strategy of corrosion prevention, and scientific insights into green materials derived from natural sources for corrosion prevention uses.

Declaration of Conflict of Interest

The authors do not have any conflicts.

Funding Statement

Authors did not collect any funds from any agencies or person for this work.

References

Abdel Hameed, R. S., Aleid, Gh. M. S., Mohammad, D., Badr, M. M., Huwaimel, B., Suliman, M. Sh., Alshammary, F., & Abdallah, M. (2022). *Spinacia oleracea* extract as green corrosion inhibitor for carbon steel in hydrochloric acid solution. *International Journal of Electrochemical Science*, 17, 221017. doi:10.20964/2022.10.31

Abuelela, A. M., Kaur, J., Saxena, A., Bedair, M. A., Verma, D. K., & Berdimurodov, E. (2023). Electrochemical and DFT studies of *Terminalia bellerica* fruit extract as an eco-friendly inhibitor for the corrosion of steel. *Scientific Reports*, 13, 45283. doi:10.1038/s41598-023-45283-0

Alimohammadi, M., Ghaderi, M., Ramazani, S. A., & Mahdevian, M. (2023). *Falcaria vulgaris* leaves extract as an eco-friendly corrosion inhibitor for mild steel in hydrochloric acid media. *Scientific Reports*, 13, 3737.

Arenas, M., García, I., & de Damborenea, J. (2004). X-ray photoelectron spectroscopy study of the corrosion behavior of galvanized steel implanted with rare earths. *Corrosion Science*, 46, 1033–1049.

Baisnab, D. K., Mukherjee, S., & Das, S. (2021). A short review on inorganic thin films from device perspective. In S. Das & S. Dhara (Eds.), *Chemical Solution Synthesis for Materials Design and Thin Film Device Applications* (pp. 231–275). Elsevier. doi:10.1016/B978-0-12-819718-9.00007-8

Bender, R., Féron, D., Mills, D., Ritter, S., Bäßler, R., Bettge, D., De Graeve, I., et al. (2022). Corrosion challenges towards a sustainable society. *Materials and Corrosion*, 73(11), 1730–1751. doi:10.1002/maco.202213140

Chhipa, S. M., Sharma, S., & Bagha, A. K. (2024). Recent development in polymer coating to prevent corrosion in metals: A review. *Materials Today: Proceedings*. doi:10.1016/j.matpr.2024.09.001

Eslamian, M., & Soltani-Kordshuli, F. (2018). Development of multiple-droplet drop-casting method for the fabrication of coatings and thin solid films. *Journal of Coatings Technology and Research*, 15, 271–280.

Faujan, N. H., Zubairi, S. I., & Baker, A. A. A. (2023). Nutritional and bioactive constituents of antioxidant and antimicrobial properties in *Spinacia oleracea*: A review. *Sains Malaysiana*, 52(9), 2571–2585. Doi:10.17576/jsm-2023-5209-08

Hassim, N., Markom, M., Rosli, M. I., et al. (2021). Scale-up approach for supercritical fluid extraction with ethanol–water modified carbon dioxide on *Phyllanthus niruri* for safe enriched herbal extracts. *Scientific Reports*, 11, 15818.

Hsieh, Y. P., Hofmann, M., Chang, K. W., Jhu, J. G., Li, Y. Y., Chen, K. Y., Yang, C. C., Chang, W. S., & Chen, L. C. (2024). Complete corrosion inhibition through graphene defect passivation. *ACS Nano*, 8, 443–448.

Jafari, Y., Ghoreishi, S. M., & Nooshabadi, M. S. (2016). Polyaniline/graphene nanocomposite coatings on copper: Electro-polymerization, characterization, and evaluation of corrosion protection performance. *Synthetic Metals*, 217, 220–230.

Jaiswal, A., Bhardwaj, S., Rai, S., Pandey, I., & Ji, G. (2023). Synthesis of ethanolic and aqueous extracts of sponge gourd peels and their application for the prevention of mild steel corrosion in saline water. *Journal of Adhesion Science and Technology*, 38, 1081–1100.

Jaiswal, Y., Rastogi, C. K., Maurya, R., Manjunatha, C., & Ji, G. (2025). Synthesis of watermelon seed extract and silica nanocomposites coatings and their utilization for the corrosion prevention of mild steel in saline solutions. *Canadian Metallurgical Quarterly*, in press, 1–16. doi:10.1080/00084433.2025.2502706

Ji, G., Singh, M. K., & Kumar, V. (2024). Deposition of layers of ethanolic extract of waste pineapple crown on mild steel through drop casting and examination of their corrosion behavior. *Journal of Solid Waste Technology and Management*, 50, 766–774.

Ji, G., Singh, S. K., & Prakash, R. (2021). Influence of the maturity of *Musa paradisica* peels on mild steel corrosion in sulfuric acid. *Journal of Adhesion Science and Technology*, 36, 1418–1438. doi:10.1080/01694243.2021.1970372

Jia, M. Y., Waterhouse, G. I. N., Zhang, J., Zhang, Z. M., Wang, J., & Yu, L. M. (2018). Comparison of the corrosion protection of electro-spun and drop-cast polyaniline microfiber coatings on carbon steel. *Synthetic Metals*, 246, 204–212.

Kumar, S., & Singh, A. (2019). An ethnobotanical, phytochemical and antioxidant activity of *Spinacia oleracea* L. *Journal of Pharmaceutical Sciences and Research*, 11(7), 2521–2525.

Lavanya, M., Suvarna, A. S., & Kumari, P. P. (2023). Adsorption and corrosion inhibition behaviour of *Pterocarpus marsupium* stem extract on mild steel in acid medium: Experimental and statistical approach. *Canadian Metallurgical Quarterly*, 63, 1335–1346.

Leslie, N., & Mauzeroll, J. (2024). Spatially resolved electrochemical measurements. In K. Wandelt & G. Bussetti (Eds.), *Encyclopedia of Solid-Liquid Interfaces* (pp. 461–478). Elsevier.

Li, X., Chen, L., Xie, B., Lai, C., He, J., Feng, J., Yang, Y., Ji, R., & Liu, M. (2023). Two semi-flexible nonplanar double Schiff bases as corrosion inhibitors for mild steel in HCl solution: Experimental and theoretical investigations. *Journal of Environmental Chemical Engineering*, 11, 110077.

Li, Y., Chen, Y., Wang, C., Li, Y., & Wu, Y. (2025). Exploring the potential of plant extracts as corrosion inhibitors: A comprehensive review. *Progress in Organic Coatings*, 198, 108915.

Li, Y., Wang, Q., Zhu, W., Ding, S., Xing, L., Bai, Z., & Wang, Y. (2025). Corrosion characteristics and mechanisms of ceramic coatings in subcritical and supercritical aqueous systems. *Ceramics International*, 51, 19743–19760.

Liu, X., Gao, Y., Guan, J., Zhang, Q., Lin, Y., Shi, C., Wang, Y., Du, J., & Ma, N. (2023). Corrosion inhibition properties of spinach extract on Q235 steel in a hydrochloric acid medium. *Arabian Journal of Chemistry*, 16, 105066. doi:10.1016/j.arabjc.2023.105066

Lou, X., & Singh, P. M. (2011). Phase angle analysis for stress corrosion cracking of carbon steel in fuel-grade ethanol: Experiments and simulation. *Electrochimica Acta*, 56, 1835–1847.

Makisha, N., & Chukhin, V. (2023). Determination of corrosion rate in galvanized pipes in centralized hot water supply systems. *Applied Sciences*, 13, 10564. doi:10.3390/app131910564

Maurya, R., Kumar, S., Pal, S. K., Ji, G., & Rastogi, C. K. (2024). Influence of watermelon seed extract on the electrochemical corrosion protection of copper in the saline environment. *Journal of Solid Waste Technology and Management*, 50, 602–613. doi:10.5276/jswtm/iswmaw/503/2024.602

Mikheev, Y. A., & Ershov, Y. A. (2018). Assignment of the $\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$ transitions to the spectral bands of azobenzene and dimethylaminoazobenzene. *Russian Journal of Physical Chemistry A*, 92, 1499–1507.

Pal, S., Ji, G., Lgaz, H., Chung, I. M., & Prakash, R. (2020). Lemon seeds as green coating material for mitigation of mild steel corrosion in acid media. *Journal of Molecular Liquids*, 316, 113797.

Pandey, I., Ullas, A. V., Rastogi, C. K., et al. (2025). Extract preparation of waste lady finger caps using ethanol, generation of extract's layers on copper through drop casting without and with NiO nanoparticles, and study of their corrosion performances in saline water. *Waste and Biomass Valorization*, 16, 971–985.

Pandey, R. K., Mishra, R., Ji, G., & Prakash, R. (2019). Corrosion prevention of commercial alloys by air–water interface grown, edge-on oriented, ultrathin squaraine film. *Scientific Reports*, 9, 13488.

Pandey, S., Mishra, K. K., Ghosh, P., Singh, A. K., & Jha, S. K. (2023). Characterization of tin plated steel. *Frontiers in Materials*, 10, 1113438. doi:10.3389/fmats.2023.1113438

Rai, S., & Ji, G. (2023). Synthesis of mint leaf extract and mint-leaf-based NiO nanoparticles, coating of extract layers without and with NiO nanoparticles on copper through drop-casting, and their analysis for the corrosion prevention in saline water. *New Journal of Chemistry*, 47, 18374–18385.

Rao, S., Smithsshree, Sowmyashree, A. S., & Rao, P. (2024). Sodium hyaluronate as an effective eco-friendly inhibitor for corrosion control. *Canadian Metallurgical Quarterly*, 1–10. doi:10.1080/00084433.2024.2375465

Semwal, A. K., Pangtey, A. S., Singh, M. K., Kumar, V., Mangla, B., Shukla, S. K., Tyagi, P., & Ji, G. (2025). Synthesis of ethanolic extract of Buddhist pine leaves and its deposition on copper's surface by drop casting for corrosion prevention in salty water. *Canadian Metallurgical Quarterly*. In press. https://doi.org/10.1080/00084433.2025.2556577.

Sharma, R., & Ji, G. (2023). Chloroform extract of Amarbel vine for developing films on copper's surface through drop casting and spin coating, and comparative investigation of their corrosion behavior in saline water. *Journal of Bio- and Tribo-Corrosion*, 9, 78.

Shekhar, C., Jaiswal, A., Ji, G., & Prakash, R. (2021). Ethanol extract of waste potato peels for corrosion inhibition of low carbon steel in chloride medium. *Materials Today: Proceedings*, 44, 2267–2272. doi:10.1016/j.matpr.2020.12.368

Shivakumar, S. S., Mohana, K. N., & Gurudatt, D. M. (2013). Inhibition performance and adsorption behavior of *Spinacia oleracea* leaves extracts on mild steel corrosion in hydrochloric acid medium. *Chemical Science Transactions*, 2(1), 163–175. doi:10.7598/cst2013.302

Sithuba, T., Masia, N. D., Moema, J., Murulana, L. C., Masuku, G., Bahadur, I., & Kabanda, M. M. (2022). Corrosion inhibitory potential of selected flavonoid derivatives: Electrochemical, molecular Zn surface interactions and quantum chemical approaches. *Research in Engineering*, 16, 100694.

Sohail, M. G., Laurens, S., Deby, F., Balayssac, J. P., & Al Nuaimi, N. (2021). Electrochemical corrosion parameters for active and passive reinforcing steel in carbonated and sound concrete. *Materials and Corrosion*, 72, 1854–1871.

Stern, M., & Geary, A. L. (1957). Electrochemical polarization: I. A theoretical analysis of the shape of polarization curves. *Journal of the Electrochemical Society*, 104, 56–63. doi:10.1149/1.2428496

Sun, Y., Zhang, Y., Xu, C., Tan, B., Li, W., Zheng, X., & Brahmia, A. (2023). Honeysuckle extract as an environment-friendly corrosion inhibitor for copper in sulfuric acid medium. *Industrial Crops and Products*, 197, 116551.

Thakur, A., Assad, H., Kaya, S., & Kumar, A. (2022). Plant extracts as environmentally sustainable corrosion inhibitors II. In L. Guo, C. Verma, & D. Zhang (Eds.), *Eco-Friendly Corrosion Inhibitors* (pp. 283–310). Elsevier. doi:10.1016/B978-0-323-91176-4.00017-9

Tiwari, M., Gupta, V. K., Singh, R. A., Ji, G., & Prakash, R. (2018). Donor–π–acceptor-type configured, dimethylamino-based organic push–pull chromophores for effective reduction of mild steel corrosion loss in 1 M HCl. *ACS Omega*, 3, 4081–4091.

Umoren, S. A., Gasem, Z. M., & Obot, I. B. (2013). Natural products for material protection: Inhibition of mild steel corrosion by date palm seed extracts in acidic media. *Industrial & Engineering Chemistry Research*, 52, 14855–14865.

Wang, H., Sun, F., Wang, C., et al. (2016). A simple drop-casting approach to fabricate the super-hydrophobic PMMA-PSF-CNFs composite coating with heat-, wear- and corrosion-resistant properties. *Colloid and Polymer Science*, 294, 303–309.

Xu, L., Su, J., Li, B., et al. (2024). Spinach leaf disease identification based on deep learning techniques. *Plant Biotechnology Reports*, 18, 953–965. doi:10.1007/s11816-024-00944-y

Xue, N., Li, W., Shao, L., Chen, Y., Wu, Y., Luo, M., et al. (2025). Characterization of monolayer and single-pass pure Cu coatings applied to 6061 T6 Al alloy and AZ31B Mg alloy substrates using high-pressure cold spray technology. *Journal of Materials Research and Technology*, 36, 252–271.

Yang, C. (2025). Facile fabrication of nickel–cobalt phosphate-based fluorine-free superhydrophobic film with anti-corrosion and self-cleaning properties on Al alloy. *Journal of Materials Science*, 60, 881–890.

Zdravković, M., Grekulović, V., Suljagić, J., Stanković, D., Savić, S., Radovanović, M., & Stamenković, U. (2023). Influence of blackberry leaf extract on the copper corrosion behaviour in 0.5 M NaCl. *Bioelectrochemistry*, 151, 108401.